Second-order LADRC to enhance Droop-based Grid-Forming converters in inductive networks

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***Abstract*—With the rise of power electronics, Grid-Forming (GFM) converter controls are proposed to control the voltage magnitude and frequency. These controls are able to provide a virtual inertia to stabilize the frequency. However, the majority of these control dynamics depends on the state of the power system network (e.g. the power system reactance). This dependance is not suitable for Grid-Forming controls. Some network states may infringe the IEEE 2800-2022 standard. To solve this issue, this work proposes a Linear Active Disturbance Rejection Control (LADRC) for Droop-based Grid-Forming controls. Its use enhances the responsiveness and robustness of Droop-based Grid-Forming controls. This work shows that by using LADRC in Grid-Forming converters a robust active power response is obtained regarding grid reactance variations in inductive networks. This robust behaviour is developed in detail through its mathematical formulation and numerical simulations.**

***Index Terms*—Control, Droop, Grid-Forming, LADRC, Robust, Virtual Inertia.**

I. Introduction

Converters are key elements of the future power system. High Voltage Direct Current (HVDC) lines, electrolysers, wind turbines and photovoltaïc panels need power converters to exchange power with the utility grid [1]. These converters are mainly controlled in Grid-Following (GFL) mode [2]. GFL converters rely on a stiff voltage to operate. This type of control is not suitable in a Power Converters Dominated Power System as it can bring instabilities if none of the converters creates the voltage reference (voltage magnitude and phase angle). To do so, Grid-Forming (GFM) controls are proposed [3]. This type of control has the role of creating a voltage reference and stabilizing the frequency in the power system. Moreover, these controls have the capability of providing inertia to the utility grid in order to enhance the frequency and rotor angle stabilities [4]–[6]. Along the years, several GFM converter control schemes have been proposed in the litterature: with/without information of the Point of Common Coupling, with/without inertia, with/without Phase Locked-Loop (PLL) and with/without droop effect [7]. The main common aspect between some of these different GFM variants is the Proportional Integral Derivative (PID) controller used [8]. The different controls presented in [8] need an accurate model used to size the gains of the PID controller. As discussed in [9], these PID controllers are usually not implemented with the derivative (D) part due to their sensitivity to noise; a control based on the past, current and the rate-of-change of the errors might not be the best control possible; and the integral term introduces some saturation and a decrease of stability margin due to phase lag. Han has noted that PID controls "cannot fully take advantage of the new compact and powerful digital processors" and "perhaps we don't need to know as much as we were told" [9]. Or Gao wondered if "modern control theory is about controlling mathematical models, instead of the actual physical plants" [10].

To the best of the authors' knowledge, the paradigm shift addressed in [9], [10] is not much in evidence in the power system domain regarding GFM control. To attenuate disturbances, some authors implement first-order LADRC that is unapplicable for inertia-based Grid-Forming converters [11]–[13]. LADRC is also applied in the domain of microgrids [14], [15]. From the short review (due to a lack of space), studies of LADRC in HVDC applications are not widely spread. There is a need to have a LADRC Inertia Grid-Forming design for HVDC applications. In [7], GFM converters based on droop control are considered for HVDC transmission and renewable energies to grid applications. [7] also points out the ease of implementation, low communication requirements and plug-play characteristics of droop-based methods. For these reasons, the benefits of LADRC on droop-based control GFM converters in HVDC applications are analyzed. In this work, only the active power control of a Droop-based Grid-Forming converter is under study and modified with LADRC.

To present the LADRC benefits for Grid-Forming controls (active power control part only), the main contributions of this work are:

- Show the working principle of LADRC
- Deduce and compare the active power transfer function between Droop-based and LADRC Grid-Forming converters
- Study the grid impedance influence on LADRC Grid-Forming control

The following work is divided into several parts. In Section II, the basic droop-based GFM control is presented. Then, the LADRC principle is explained in Section III. Afterwards, the system proposed to enhance the GFM converter is presented in Section IV. In Section V, numerical experiments are undertaken on a Thévenin equivalent power system using MATLAB/Simulink followed by a discussion on the results (Section VI). Finally, the conclusion is drawn in Section VII.

II. Droop-based GFM control

In this section, a general explanation of the droop-based GFM control is made. An inertial droop-based GFM controller is chosen without PLL to restrict the analysis made in this work. This control is illustrated in Fig.1. It is a PID control based exclusively on proportional or integral terms.

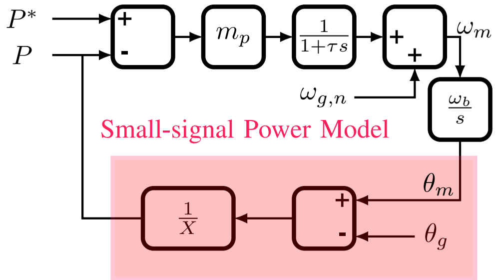

Fig. 1. Inertial droop-based GFM controller without PLL chosen in this work for analysis with the droop coefficient (m_p), the time constant of the first order filter (τ), the nominal grid frequency ($\omega_{g,n}$), the controlled frequency/phase (ω_m/θ_m) and the grid phase (θ_g)

From Fig.1, it is possible to derive the small-signal transfer function between the measured active power (P) and the active power setpoint (P^*):

$$\frac{P}{P^*} = \frac{m_p \omega_b}{X\tau s^2 + Xs + m_p \omega_b} \tag{1}$$

Equation (1) is based on the small-signal power model:

$$P = \frac{\sin(\theta_m - \theta_g)}{X} \approx \frac{\theta_m - \theta_g}{X} \tag{2}$$

with $X = X_g + X_T + X_f$, the reactances shown in Fig.3 and the other parameters are defined in Fig.1 and Tab.I. From Fig.3, several assumptions are made using this small-signal model:

- It neglects the LC filter, usually used for 2-Level VSC's, in order to simplify the analysis.
- It also considers a power transmission system (the resistance is much smaller than the reactance).
- The grid is modeled by a Thevenin equivalent of a reactance X_g, a resistance R_g and a voltage V_g.

For an input ($U(s)$) and an output ($Y(s)$), the second order canonical transfer function form is:

$$\frac{Y(s)}{U(s)} = \frac{1}{\frac{s^2}{\omega_n^2} + \frac{2\zeta}{\omega_n}s + 1} \tag{3}$$

with ω_n, the natural pulsation and ζ, the damping factor.

By identification between (1) and (3),

$$\omega_n = \sqrt{\frac{m_p \omega_b}{\tau(X_g + X_T + X_f)}} \tag{4}$$

$$\zeta = \frac{1}{2}\sqrt{\frac{X_g + X_T + X_f}{m_p \omega_b \tau}} \tag{5}$$

The network impedance (X_g) has an impact on both the natural pulsation and the damping factor. When the Short Circuit Ratio of the network (SCR) increases (resp. decreases), the network impedance decreases (resp. increases) [19]:

$$SCR = \frac{1}{X_g}\ [pu] \tag{6}$$

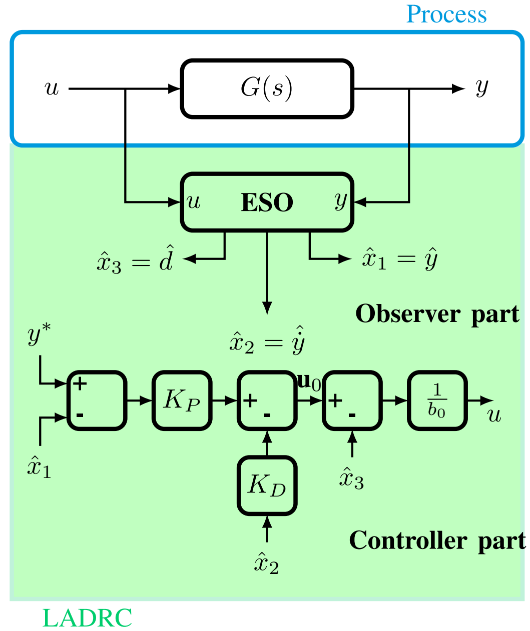

Fig. 2. Second-order LADRC represented with the observer and controller parts

The dynamic behaviour depends on the grid strength. This type of control is not robust against impedance variations and thus not suitable for active power regulation.

III. Linear ADRC Fundamentals

To cope with this reactance dependance behaviour, the LADRC is used in this work. This section covers the theoritical background of LADRC and shows how this control technique can improve the dynamic of droop-based Grid-Forming control [20].

Unlike the PID control, LADRC is a control method relying on an **Extended** State Observer (ESO). Its purpose is to estimate the process states **along with** the possible **disturbances** applied to the plant. A general second-order LADRC applied on a second order plant ($G(s)$) is shown in Fig.2.

To use the LADRC, it is necessary to:

1) Have an observable plant
2) Know the order of the plant (e.g. first, second, third order)
3) Estimate its critical gain constant, b_0

Considering the input ($U(s)$) and the output ($Y(s)$), $G(s)$ is defined, using the Laplace operator (s), as:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{\alpha}{s^2 + \gamma s + \delta} \tag{7}$$

with positive constants α, γ and δ.

In temporal form, it can be expressed as:

$$\frac{d^2}{dt^2}y(t) + \gamma\frac{d}{dt}y(t) + \delta y(t) = \alpha u(t) \tag{8}$$

In LADRC, the estimated disturbance is composed of endogeneous and exogeneous elements. There is no difference between an internal parameter variation and an external input disturbance. For any general disturbance ($d(t)$):

$$\frac{d^2}{dt^2}y(t) = b_0\ u(t) \underbrace{+\Delta b\ u(t) - \delta y(t) - \gamma \frac{d}{dt}y(t)}_{d(t)} \\ = b_0 u(t) + d(t) \tag{9}$$

with $\alpha = b_0 + \Delta b$ composed of a known part (b_0) and a variable part (Δb). The critical gain (b_0) is usually estimated in advance.

A. Extended State Observer design

To estimate the general disturbance, ESO is used. In an ESO, the disturbance is counted as a state variable in the process [21]. For a second-order plant to be controlled, the designed ESO is a third order process. In this case, it has the following form:

$$\begin{pmatrix} \dot{\hat{x}}_1(t) \\ \dot{\hat{x}}_2(t) \\ \dot{\hat{x}}_3(t) \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \end{pmatrix} + \begin{pmatrix} 0 \\ b_0 \\ 0 \end{pmatrix} u(t) + \begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix} (y(t) - \hat{x}_1(t)) \tag{10}$$

$$\hat{y}(t) = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \end{pmatrix} \tag{11}$$

with l_1, l_2, l_3, the observer gains.

To not interfere with the controller part of LADRC, it is important to choose l_1, l_2 and l_3 such that the observer modes (ω_0) are at least 10 times higher than the controller modes (ω_c). If it is not the case, there will be interferences between the dynamics of the controller and the plant to be controlled [23]. In this work, the three modes of the observer are set around ω_0 [22]. The observer gains are:

$$\begin{cases} l_1 = 3\omega_0 \\ l_2 = 3\omega_0^2 \\ l_3 = \omega_0^3 \end{cases} \tag{12}$$

B. Controller design

From Fig.2, the controller part is studied. It is composed of three elements:

1) K_P, the proportional gain
2) K_D, the derivative gain
3) The disturbance removal

The two first terms look like simple proportional gains (as in a PID controller). However, the compared value is not the actual output (or its derivatives) but an estimation of it.

$$e_{K_P}(t) = K_P(y^*(t) - \hat{y}(t)) \tag{13}$$

Based on $e_{Kp}(t)$, the estimated derivative is removed.

$$u_0(t) = e_{K_P}(t) - K_D\dot{\hat{y}}(t) \tag{14}$$

After these two steps, the disturbance-free input to the plant ($u(t)$) is found. It is important to remove the estimated disturbance ($\hat{x}_3(t) = \hat{d}(t)$) from the system to ensure a proper functioning of the controller if subjected to disturbances.

$$u(t) = \frac{1}{b_0}(u_0(t) - \hat{d}(t)) \tag{15}$$

By using (13) in (14), both in (15) :

$$b_0 u(t) = K_P(y^*(t) - \hat{y}(t)) - K_D\dot{\hat{y}}(t) - \hat{d}(t) \tag{16}$$

Finally, incorporating (16) in (9) under perfect observer conditions, the controller behaviour is reduced to:

$$\frac{d^2}{dt^2}y(t) = b_0 u(t) + d(t) \\ = K_P(y^*(t) - \hat{y}(t)) - K_D\dot{\hat{y}}(t) - \hat{d}(t) + d(t) \\ \approx K_P(y^*(t) - y(t)) - K_D\dot{y}(t) \tag{17}$$

In Laplace domain, it gives:

$$\frac{y(s)}{y^*(s)} = \frac{K_P}{s^2 + K_D s + K_P} \tag{18}$$

The controller parameters can be settled as:

$$\begin{cases} K_P = \omega_c^2 \\ K_D = 2\omega_c \end{cases} \tag{19}$$

without forgetting $10\omega_c < \omega_0$ [23].

When designed in a rigorous way, the findings of this method are:

1) The total disturbance ($d(t)$) is removed from the process
2) There is no derivative actions amplifying noise in the controller part
3) The resulting behaviour does not rely on the plant
4) It is necessary to estimate the critical gain (b_0) and the plant order in advance.

A second-order LADRC is proposed to be used in an inertial Grid-Forming converter control thanks to these properties.

IV. System considered in this work

The scheme of the studied system is shown in Fig.3. It represents a VSC converter linking an HVDC line to an High Voltage Alternating Current (HVAC) system. The power grid is modeled as an ideal voltage source behind a network impedance in this work. The elements are parametrized in Tab.I [25].

Fig.4 shows the control used in this work to create the modulation signals (m_a, m_b, m_c). It is a conventional Grid-Forming control with the LADRC stage added. A virtual transient impedance is added to damp the oscillation modes of inductive networks. It creates direct and quadrature voltage components (Δv_{dq}). The active and reactive power loops are decoupled in inductive networks in small-signal analysis [17].

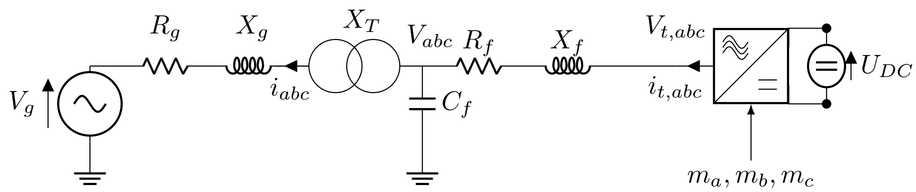

Fig. 3. Testbench used in this work (one-line representation) considering a 2-Level VSC inverter

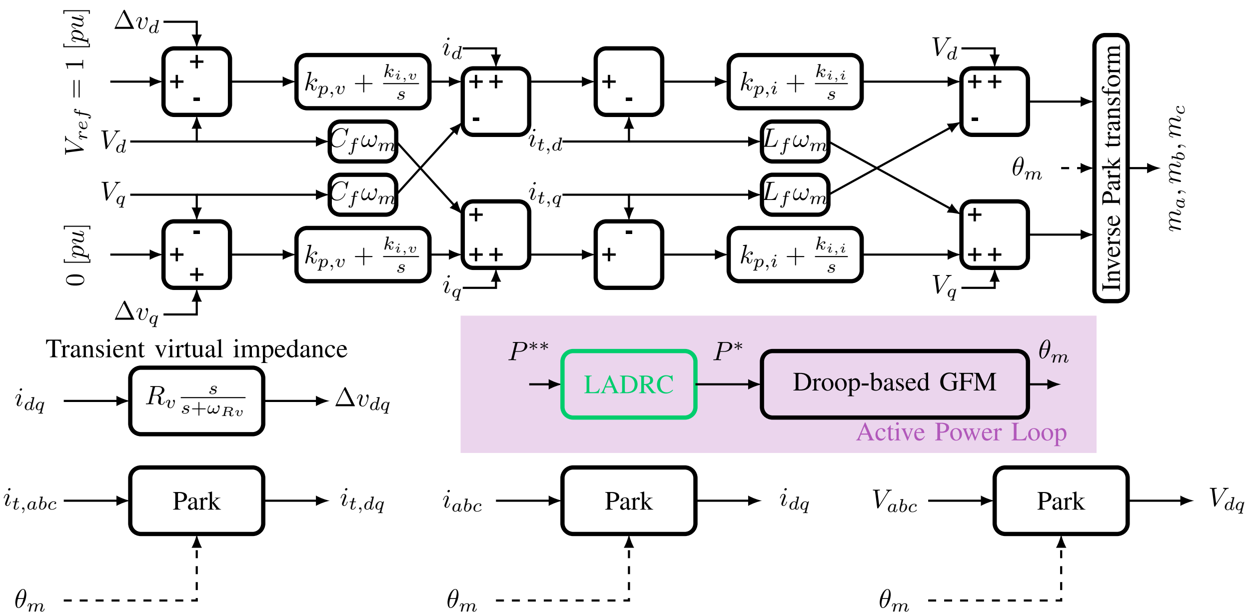

Fig. 4. Basic principle of the direct voltage Grid-Forming control used in this work with the added layer in green to enhance the active power dynamics of inertial Grid-Forming controls

TABLE I
PARAMETERS USED FOR THE NETWORK ELEMENTS

Element studied	Value
Base chosen	$S_B = 1000$ MW $U_B = 230$ kV (grid side)
Nominal frequency Converter type	50 Hz 2-Level VSC (6 pulses) Switching frequency: 1350 Hz
DC system	200 kV ($U_{DC} = 1$ pu)
Phase reactor	X_f = 0.15 pu R_f = 0.015 pu
Filter capacitor	C_f= 0.066 pu
AC transformer	Yg/D1, 200 MVA, 230:100 kV, X_T = 0.15 pu
AC system	230 kV ($V_g = 1$ pu), 50 Hz Network reactance (X_g) : scenario related Network resistance (R_g) : 0.033 pu
Control parameters	$R_v = 0.09$ pu $\omega_{Rv} = 60$ rad/s $\tau = 0.238$ s $m_p = 0.0238$ pu $[k_{p,i}; k_{i,i}; k_{p,v}; k_{i,v}] =$ $[0.73; 1.19; 0.52; 1.16]$ pu $K_P = 52.35$ $1/s^2$ $K_D = 33.6$ 1/s $\omega_0 = 100$ rad/s

The reactive power control loop is represented in Fig.4. The results shown in this work are not impacted by the reactive power loop due to the decoupling effect in inductive networks.

The active power control loop proposed is illustrated in Fig.4. The analysis of an additionnal control layer on the active power control loop is made. The objective is to create an active power reference (P^*) for the droop-based Grid-Forming control managing the phase of the inverter (θ_m). This active power reference is given by another control layer based on LADRC with the active power reference, P^{**}, as input. The proposed control details are illustrated in Fig.5. The process under consideration (in blue) is composed of the power model (red part) and the droop-based Grid-Forming control, whose general behaviour is shown in (1).

When LADRC is added, a new transfer function is found between the active power produced (P) and the reference (P^{**}).

$$\frac{P}{P^{**}} = \frac{1}{\frac{1}{K_P}s^2 + \frac{K_D}{K_P}s + 1} \tag{20}$$

considering the observer estimations are ideal.

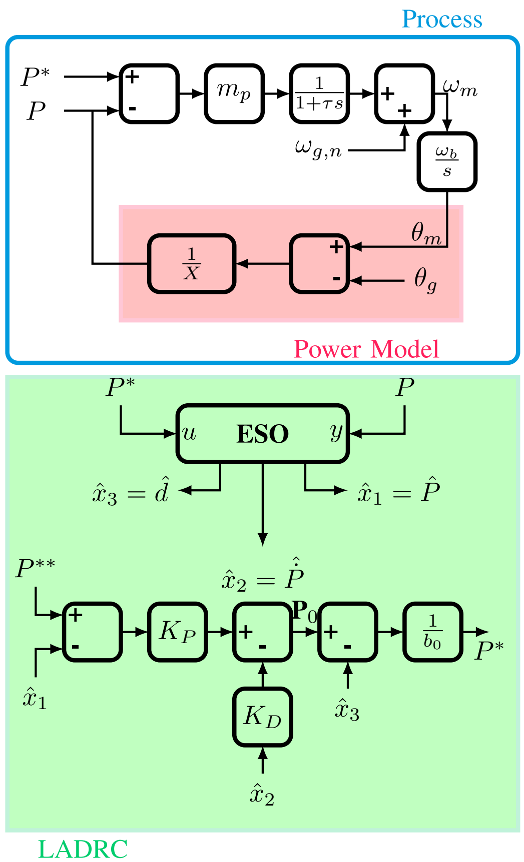

Fig. 5. Droop-based GFM controller chosen in this work for analysis with the LADRC part represented in green

V. Numerical Experiment

This numerical experiment is based on the testbench presented in Section IV. It is an EMT-based simulation considering the detailed switching model of the 2-Level VSC converter. A step is applied to the active power reference of the 2-Level VSC converter at time $t = 4\ [s]$. It has a $0.3\ [pu]$ magnitude. The resulting active power response is observed under four different cases:

Case 1 : Droop-based Grid Forming and $SCR = 3\ [pu]$
Case 2 : Droop-based Grid Forming and $SCR = 1.5\ [pu]$
Case 3 : LADRC + Droop-based Grid Forming and $SCR = 3\ [pu]$
Case 4 : LADRC + Droop-based Grid Forming and $SCR = 1.5\ [pu]$

The added LADRC layer is designed to have an overdamped active power response to avoid stimulating oscillation modes (Tab.I). The active power response is shown in Fig.6.

From Fig.6 and without LADRC, the active power response dynamic behaviour depends on the change of the grid reactance occuring in the network. However, when LADRC is added, the active power response keeps the same global behaviour. It shows the disturbance rejection ability of LADRC as the SCR variation does not impact the active power response anymore.

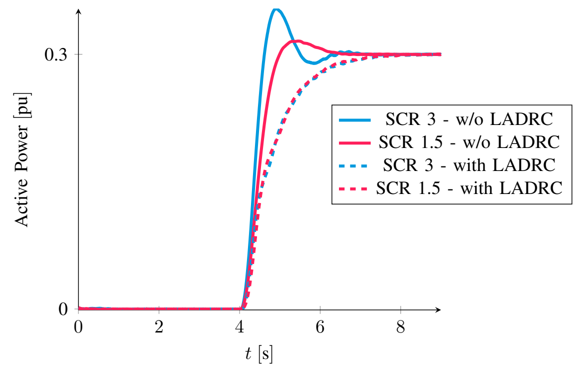

Fig. 6. Results from the realistic numerical experiment representing a HVDC infrastructure. The four active power responses linked to the four cases are shown. For dashed lines, the LADRC is activated.

VI. Discussion

As shown in this work, LADRC offers the possibility to control the *real* world instead of a *pure model*. It is not necessary to model every detail of the world under study when using LADRC. These details are considered as disturbances in the control. Two interesting applications can use LADRC in power systems about the converter control.

First, LADRC could help in controlling converters provided by manufacturers. Due to IP's (Intellectual Properties), manufacturers do not provide details about the converter they are selling. For a PID-based control, it could be difficult to control such converter as an accurate model is needed. However, for LADRC-based control, the needed informations are less strict. The useful informations are more global and do not treat the IP's of the manufacturers.

Secondly, LADRC could help in controlling converters with respect to the grid itself. The grid cannot be considered as fixed. It is dynamic. Therefore, the quantities are varying such as the reactance (e.g. open/close lines), the current (e.g. faults, loads), the voltage (e.g. dips, sags) or the frequency (inertia related). Faced to this dynamic grid, it is important to handle these variations automatically in the control of the converters without trying to model each detail inside the power system. It is of utmost importance when talking about the energy transition.

This work is a first promising step in second-order LADRC Grid-Forming controls field. This study is limited to a single active power Grid-Forming converter without protection algorithms (there are no large disturbances in this work). As stated in [16], these internal loops may interact with the system. Moreover, the dynamics of the ESO are disregarded (e.g. observer bandwidth choice). The dynamics of the estimates are not studied in detail in this work. Delays inside the system need to be concerned too as Pulse-Width Modulation introduces delay jeopardising the stability [24]. Finally, DC side dynamics have to be extended to study the interactions between AC and DC sides of the converter.

VII. Conclusion

In this work, LADRC has been introduced for HVDC lines applications. The benefits of using a LADRC in the Droop-based GFM control have been shown. First, the drawbacks of the inertial Droop-based GFM (without PLL) have been introduced. Then, the LADRC theory has been explained to understand why this method could be used to control converters. Afterwards, the LADRC has been jointed to the Droop-based GFM control to improve the responsiveness with respect to the grid impedance. The LADRC has been parametrized using a simple Power Model. Based on this simple power model, the same parameters have been used in realistic numerical experiments. From the extracted results, a discussion has emerged and some perspectives of this LADRC are proposed.

This work showed the possibility to design a control that is less dependent on the reactance of the grid without losing the inertial effect [18]. It paves the way to a control-based instead of a model-based controller in future power systems. Based on this, it could solve issues from the manufacturers field to the grid dynamics area. Further work will assess in studying the frequency behaviour of the total LADRC chain (as partially done in [23]) to fully exploit LADRC's capabilities in the future (e.g. to better understand the inertia emulation). It will provide a better understanding of the delays or dynamics of ESO observations on Grid-Forming controls. Moreover, this work proposed a hybrid LADRC-PID control. Further studies will consider the utility (or not) of using the LADRC on a PID GFM control (as done in this work) or directly on the converter.

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