An Overview on the Recent Advances of the Voltage Source Converter Control Modes in Terms of their Roles in Transmission Grid Ancillary Services

Rayane MOUROUVIN, Jing DAI, Seddik BACHA, Didier GEORGES and Abdelkrim BENCHAIB

Abstract−Voltage Source Converters (VSC) are expected to be one of the major actors in future AC transmission grids. Their role includes the interconnection of renewable energy, from distributed sources such as residential PV to large Offshore Wind Farms (OWF) using HVDC. With the ongoing decommissioning of traditional power plants with their synchronous generators, VSCs must now bring support functions to the grid. The aim of this paper is to review the different grid services that can be achieved through VSCs and discuss their compatibility with the state-of-the-art VSC controls especially the so-called grid-following and grid-forming controls. After presenting the upcoming issues of future grids and classifying the main VSC controls, this paper deals with the different additional control laws which make it possible to support the AC grid. Some recommendations regarding future grid services classifications and power and energy requirements are given. A comparative table is also proposed to assess the role of the different control modes.

***Keywords*− Ancillary service, grid-following, grid-forming, renewable energy, voltage source converter (VSC).**

Nomenclature

VSC	Voltage Source Converters.
OWF	Offshore Wind Farms.
PSS	Power System Stabilizers.
RoCoF	Rate of Change of Frequency.
SG	Synchronous Generators.
SM	Synchronous Machines.
AVR	Automatic Voltage Regulator.
SCL	Short Circuit Level.
SCR	Short Circuit Ratio.
SCC	Short Circuit Contribution.
PWM	Pulse Width Modulation.
PLL	Phase Locked Loop.
MMC	Modular Multilevel Converters.
FRT	Fault Ride Through.
FFR	Fast Frequency Response.
DSE	Dynamic State Estimation.
POD	Power Oscillation Damping.
ESS	Energy Storage System.
VSM	Virtual Synchronous Machine.

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I. Introduction

Power systems now encounter massive changes in terms of generation, transmission and distribution of electricity. In the European Union, the share of renewable energy in electricity generation is expected to rise constantly for the next decades [1], in a worldwide attempt to tackle climate change [2]. In particular, at the transmission-grid level, especially in Europe, many HVDC systems have been built to exchange energy across long distances and interconnect Offshore Wind Farms (OWF) to the mainland [3]. At the distribution-grid level, Power Electronics (PE) converters are used to integrate renewable power sources and new types of loads, such as islanded systems and electric vehicles [4]. These changes will lead to an evolution of the operation of power systems, where PE-interfaced sources and loads will replace a large number of Synchronous Generators (SG) [5].

To ensure stability of such power systems in the future, the PE converters will have to play the roles of traditional SG. This topic has been discussed for years in the scientific community [6] and draws public attention [7]. In particular, the current methods we know to operate and secure the power systems will have to evolve. In order to understand the necessary conditions to operate these PE-dominated grids, we need to analyze the elementary functions that are brought by synchronous generators. Traditionally, the grid stability and reliability is ensured by implicit actions from generators themselves and by specific actions which require additional controls, such as primary frequency support or Power System Stabilizers (PSS) or dedicated equipment such as synchronous condensers or FACTS. In various regions of the world, some of these functions are allocated using ancillary services market [8], [9], [10]. In parallel, with the growing role of PE-based converters, more and more studies now focus on the potential contributions of VSCs to the operation of 100% PE-based grids, such as micro grids [11], offshore networks [12] and HVDC transmission grids [13], [14]. However, these papers only deal with the control options, instead of addressing the needs of the grid. In the last decades, a consistent classification of the power system stability issues has been used as a reference for transmission grid operability and stability [15]. But it is only recently that this classification has been adapted to take into account the increasing role of VSCs in the grid [16], but no classification of the existing control solutions for any of those issues is achieved.

More recently, the impacts of VSC control to provide specific support functions to the common system stability issues was discussed in [17], which only focuses on vector-controlled, also named current-source controlled, VSCs and only briefly mentions the role of grid-forming. On the other hand, some recent studies [18], [19] did compare the role of different grid-forming implementations in multi-machine systems but did not compare them to the most commonly used current-source mode. Indeed, even though there has been some research conducted on classifying those different grid forming controls [20], [21], there is still a missing piece between what can be achieved in terms of ancillary services, i.e. from the grid point-of-view, by the different VSC control modes. In [22], the authors study the evolution of power systems and how it will affect the existing ancillary services. Although it provides insightful review of the implementation of new ancillary services, it does not focus on the control aspects of the VSCs. In [23], the authors present a review of the support functions of VSC for micro grids, but this work is specific to low-voltage systems and do not discuss wide-area issues such as frequency support or power oscillation damping for instance. Some papers proposed a review of specific support functions of VSCs for transmission grids, such as inertia [24], short-circuit contribution for unbalanced faults [25] and power sharing options, both active and reactive, hence integrating grid-forming controls [26]. In addition, more recent reports were published about the role of grid-forming controlled VSCs in grid support functions [27], [4]. However, no comparison is clearly drawn with the most commonly-used current-source controls. In parallel, the role of the grid-forming controlled VSCs in enhancing the PE-based sources penetration limits using modal analysis have been the topic of several studies [28], [29], [30] but these papers are mainly based on simplified systems and it is hard to extract the precise role of each support function when applied to more complex systems. To the authors' best knowledge, there is no review in the literature which focuses on the different VSC control options for the needed support functions from the transmission grid perspective.

In this paper, we gather information about the existing grid services that are currently provided by synchronous machines and that will be needed from the VSCs to ensure a smooth transition to hybrid grids with remaining synchronous units and a high proportion of PE-based converters. The novelty of the paper is to propose a comprehensive comparison of the converter control modes, i.e. Current-source and voltage source modes, not only in terms of converter-level control performances, but also in terms of the potential ancillary services they can provide to the grid.

The paper is organized as follows. In Section 2, we describe the ongoing evolution of power system production and transmission structures and the role of SGs in power system stability. In Section 3, the VSC control modes are introduced and an updated classification is defined for the transmission grid. In Section 4, the role of the VSC in both current-source and voltage-source modes are explored in terms of the grid support functions. Finally, an overview of the differences is drawn in Table 3 and discussed in Section 5.

II. IMPACTS OF THE REPLACEMENT OF SYNCHRONOUS GENERATORS BY POWER ELECTRONICS-BASED STATIONS

The role of the SGs in power systems has been studied for decades [31], [32], and their services to the grid are summarized in this section, in particular, frequency support, reactive power support, contribution to system strength, short circuit contributions and power oscillation damping.

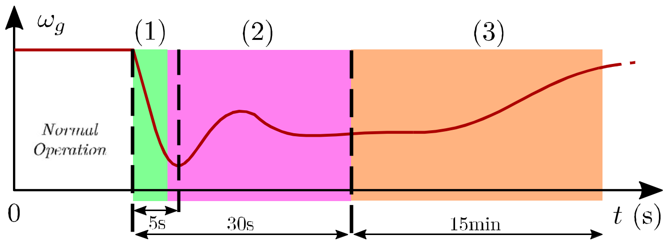


Fig. 1: Different mechanisms with distinctive time scales of the grid frequency when encountering an active power disturbance. (1) Is for inertial response, (2) is for primary frequency control and (3) is for secondary frequency control.

A. *Frequency support*

Traditionally, the grid frequency is mainly supported by the synchronous generators which provide a frequency response following a contingency in the form of an unbalance between the generation and the load. A typical frequency profile of such response is given in Figure 1, where the different mechanisms are highlighted in terms of the time constant:

- Inertial response: The physical law imposes that, in case of a frequency deviation, the SG instantaneously releases the kinetic energy in its rotor, which reduces the Rate of Change of Frequency (Ro Co F).
- Primary frequency control: The speed governor, usually in form of a droop, adjusts the mechanical power from the prime mover in the time scale of 30 seconds, in order to stabilize the frequency.
- Secondary frequency control: The secondary frequency regulator, with a time constant of 15 minutes, adjusts the mechanical power of the synchronous generators of the control area where the disturbance originates, in order to bring back the grid frequency to 50 Hz and restore the power exchange between the control areas.

B. *Reactive power support*

The reactive power support refers to the capacity of a given system to provide some reactive power which is used to maintain the grid voltage. For this, the SG are equipped with an Automatic Voltage Regulator (AVR), which observes the voltage magnitude and adjusts the reactive power accordingly. Indeed the reactive power compensation is used to maintain the grid voltage within acceptable limits. This support is often seen as an ancillary service from the TSO point of view [33]. It can be separated in two types [33], [34] according to the time scales:

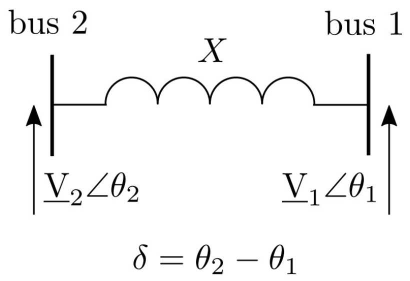
- Dynamic support: it refers to the capability to control the bus voltage magnitude following a disturbance. The Belgian TSO Elia defines it as a voltage control that "is activated automatically by the user's production units" [34]. This is provided by the SGs' AVRs for instance;
- Static support: it refers to changes of reactive power

references in a given grid in order to support the AC grid voltage at all nodes. This corresponds to a centralized action dictated by the regional TSO. It is triggered "either automatically or manually depending on the situation" [34].

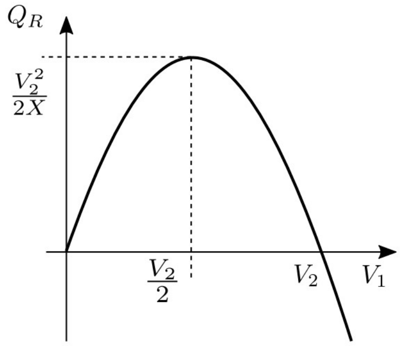
To illustrate the role of reactive power in voltage control, a simple case system is given in Figure 2a. The reactive power received at the bus 1, denoted by QR can be calculated, with phasor assumptions [35], as:

$$Q_R = \frac{V_1}{X}(V_2 \cos\delta - V_1)$$

$$Q_R \approx \frac{V_1}{X}(V_2 - V_1)$$



(a) Simplified view of a two-bus system interconnected with a purely inductive line.



(b) Reactive power evolution around small disturbances (δ = 0).

Fig. 2: Approximation of the reactive power steady-state value depending on the voltage magnitude [35].

Figure 2b gives the evolution of Q_R using (2) and shows the importance of acting on the reactive power to control the AC voltage magnitude. In practice in traditional power systems, the operating points of SGs are determined in power flow studies in order to avoid line congestions and have acceptable voltage magnitude levels [36] but the TSOs also rely on automatic voltage control actions to maintain the bus voltages following unexpected disturbances.

C. System Strength

The system strength, or voltage stiffness, is a metric that quantifies the capability of a given AC bus to maintain the bus voltage around its nominal set point, in terms of both voltage magnitude and phase angle. In its 2016 System Operability Framework [37], the British TSO National Grid gives the following definition in the voltage management section:

"System strength is a regional characteristic which can be expressed as short circuit level (SCL), measured in kA. It provides an indication of the local dynamic performance of the system and behaviors in response to a disturbance."

With this definition, it is clear that a bus connected to a voltage source, such as an SG, has a stiff voltage since the generator controls its voltage magnitude thanks to its AVR. To quantify the system strength of a grid dominated by SG, the power system community has used for decades the notion of Short-Circuit Level (SCL) or Short-Circuit Ratio (SCR) [38], defined as the amount of fault current that will be injected to the bus in case of a fault normalized with the bus base power. This means that for a given voltage, the higher the SCR is, the closer it is to SGs since the equivalent impedance to the faulty bus is smaller. Nowadays, the system strength is considered as a rising issue because a low value of SCR can create stability problems due to the PE-based source controllers [16].

Although the SCR is a single notion to study the system strength, it actually contains two different power system issues: the system strength at the given bus discussed in this subsection, and the contribution to the short-circuit current, discussed in the next subsection.

D. Short-circuit contributions

The voltage-source behavior of the machine and its large overcurrent capacity make it possible to inject a high short-circuit current in case of a fault, which is essential for the proper operation of the protective relays. The SGs inherently provide a Short-Circuit Contribution (SCC) when a fault occurs. Indeed, during the first instants following the fault, the machine remains connected and injects a fault current which can be as high as 500% of the nominal current [39]. This behavior is illustrated in Figure 3. As shown in this figure, from the point of view of the faulty bus, all the fault currents from the SG and the other AC grid fault currents converge to it. These fault currents are valuable because they are used to detect and locate the fault in the AC grid. Note that, similar to the inertial response, the short-circuit contribution is also a natural behavior of the SG, i.e. No additional control is needed to realize this. However, this feature is based on the voltage-source behavior of the SG which still relies on the AVR performances during the fault.

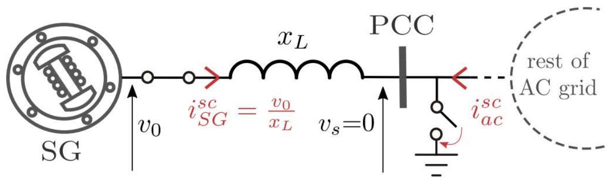


Fig. 3: Grid-connected synchronous generator response when encountering a fault at its point of coupling.

E. Power oscillation damping

Power oscillations refer to low-frequency oscillations, in the range of 0.1 to 1 Hz, which are due to structural limits of the system when certain large-scale disturbances (synchronous generator loss, line tripping, etc.) occur. They are mainly due to the poor damping of low-frequency modes which exist in power systems where the loads and production units are not regularly distributed or where the transmission lines are relatively long [40]. These oscillations must be taken care of because they provoke power oscillations which generate more losses and can cause the tripping of lines. To solve this problem, the Power System Stabilizer (PSS) [35] can be added to the AVR to improve the damping of power oscillations.

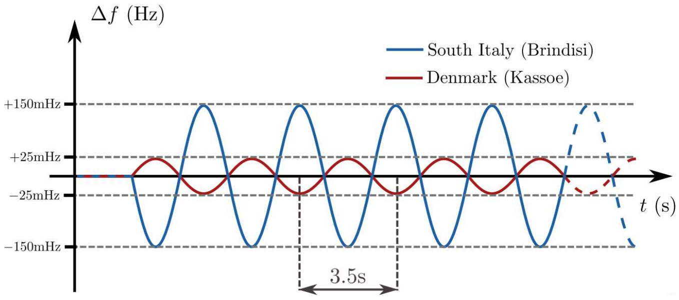


Fig. 4: Illustration of the inter-area oscillation event of the 3rd of Dec. 2017 in the European grid. Based on [41].

However, this problem is still an up-to-date topic because the locations of the SGs equipped with PSSs plays a major role on the damping factor of the whole system. An illustrative case of inter-area oscillations which occurred in Europe in 2017 [41] is given in Figure 4. In this example, 0.3Hz oscillations were noticed by European TSOs in December 2017 between the Northern and Southern parts of Europe. The root cause was not a single large-scale event but rather a sum of different low-risk factors in South Italy.

This event shows the importance of the PSSs allocation, since the disturbance severity can be drastically different depending on the grid node, as described in Figure 4.

F. Consequences of the SG dismantlement on system stability

As synchronous generators are being progressively replaced by PE converters, all the functions described earlier in this section will have to be fulfilled in transitional grids with high proportion of PE and the remaining SGs. This issue is gaining more and more attention from academia [42] and industry [43] across the world.

In 2017, a list main challenges on power system stability were highlighted by European TSOs [43], of which the following items are related to the replacement of SGs by PE-based generation units:

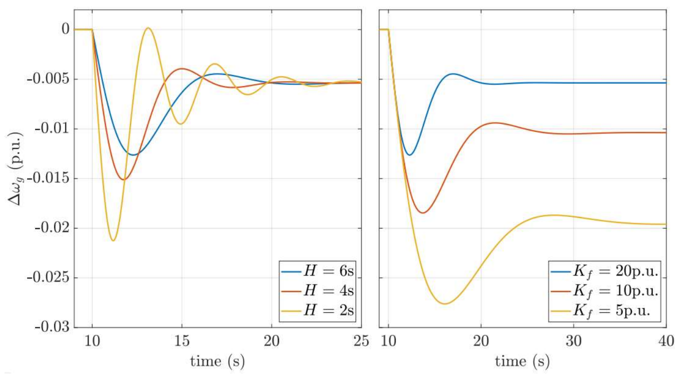


Fig. 5: Effects of decreasing inertia and primary frequency reserves in AC grid frequency ω_g. H is the inertia constant and K_f the primary frequency droop gain. The nominal case (blue line) is H=6s and $K_f = 20p.u.$

1. Decrease of inertia;
2. Reduction of transient stability margins;
3. Wrong participation of PE-based generators in frequency containment;
4. Loss of devices in the context of Fault-Ride-Through (FRT) capability;
5. Lack/excess of reactive power;
6. Voltage dip-induced frequency dip;
7. Introduction of new power oscillations and loss of existing power oscillation dampers (such as PSS of SGs).

Table. I
INERTIA CONTRIBUTIONS OF DIFFERENT COUNTRIES IN EUROPE FOLLOWING ENTSO-E 2030 SCENARIO [4]

Inertia (s)	Countries
H < 2s	Germany, Italy, Ireland, Spain, UK.
2s ≤ H < 3s	Austria, Switzerland.
3s ≤ H < 4s	Finland, France, Norway, Sweden.
H ≥ 4s	Hungary, Poland, Serbia.

Taking the first one for instance, the inertia of most of the European countries is expected to decrease due to the increasing of renewable generation in the electricity mix. The expected equivalent inertia constants of different European countries by 2030 is given in Table 1.

This table shows that countries which would rely on massive renewable sources such as Southern European countries with solar power or Northern Sea countries with wind power, would have a low inertia contribution. On the other hand, Central European countries which still rely on coal-powered plants would have a much higher inertia. Finally, countries that have started to introduce renewables in their electrical systems but still rely on low-carbon power plants, either hydro or nuclear, would be in-between.

In consequence, there is a need to counterbalance the impacts of dismantling current power plants in order to maintain the system operable. In Figure 5, we illustrate the consequences of decreasing inertia and the deployment of primary frequency reserves following an active power load step in the frequency deviation of a two-bus system with one SG and one load. The lack of inertia may cause the tripping of certain components due to an excessive value of RoCoF.

G. Opportunity of the use of power electronics in transmission grids

Even if many challenges arise due to this grid transition, PE-based sources may offer innovative solutions since these interfaces are much more controllable and faster than typical SGs. In addition, as illustrated in Table 2, the integration of renewable energy sources such as OWF, here denoted as wind power plants, the grid-side converter rarely works at its maximum rated power due to wind intermittency mostly. The average active power set point can be derived as follows. The maximum active and reactive power headroom from this average set point are then calculated while assuming the initial reactive power set point is $q^* = 0$:

Table. II
COMPARISON OF THE CHARACTERISTICS OF A SG AND A VSC IN TERMS OF AVAILABLE POWER HEADROOM AND ENERGY FOR SUPPORT FUNCTION PROVISIONS.

Features	Symbol	Wind Power Plant	Thermal Power Plant
Installed capacity, from [44]	S_b	2500 MVA	1000 MVA
Operating hours, from [44]	t_{op}	2000 h	5000 h
Yearly produced energy, from [44]	W_y	5000 GW.h	5000 GW.h
Overcurrent capability, from [45]	i_{max}	110%	500%
Average power set point	p^*_{avg}	0.23 p.u.	0.57 p.u.
Max. active power headroom	P_{hr}	0.77 p.u.	0.43 p.u.
Max. reactive power headroom	Q_{hr}	0.97 p.u.	0.82 p.u.

$$p_{avg}^* = \frac{t_{op}}{t_{year}} = \frac{t_{op}(h)}{8670}$$
$$P_{hr} = S_b \times (1 - p_{avg}^*)$$
$$Q_{hr} = S_b \times \sqrt{1 - {p_{avg}^*}^2}$$

It appears that the active power at the operating point of the converter is quite low, here assumed to be at $p_{avg}^* = 0.23\ p.u.$. In consequence, there would be a lot of power headroom, both active and reactive, available in average, to counterbalance the progressive dismantlement of SGs and the upcoming challenges listed above. This will still require to implement additional control options, which are summarized in Sections 3 and 4.

III. Converter-Level Control Modes

This section presents the existing converter control modes classified into two main categories: current- source mode and voltage-source mode. The state variables we use in the control schemes are based on the equivalent VSC with its LC filter described in Figure 6.

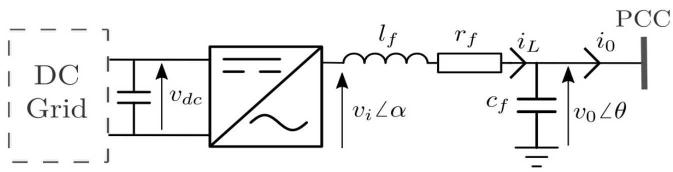


Fig. 6: Equivalent electrical circuit of a Voltage Source Converter (VSC) between its AC and DC interfaces.

A. *Current-source mode*

The current-source control, also known as grid-following or grid-feeding control, is the most commonly used method, where the converter imposes both the active and the reactive power, independent of the grid frequency and voltage. The controller receives the power set points and yields the reference for the current to be injected into the grid. Thus, the converter works as a current source, i.e. the current (and hence the active and reactive power) is controlled while the voltage magnitude and the frequency is free to change. Note that the power reference itself can be varying due to other factors, e.g. the intermittency of renewable energy sources, or an over-layer controller providing some grid service.

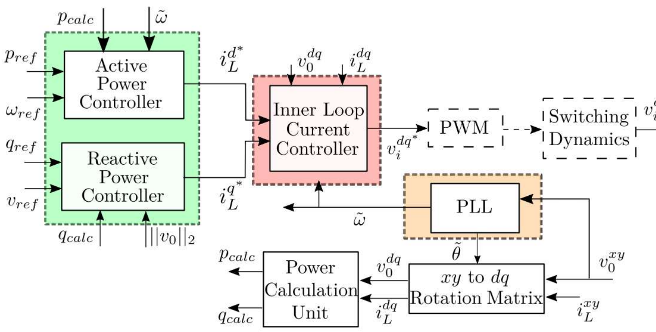


Fig. 7: VSC cascaded structure control scheme in current-source mode.

A classical implementation of the grid-following control is shown in Fig. 7. The voltage at the point of common coupling (PCC) is denoted as v0, while the voltage synthesized by the converter as v_i. A reactor lf is placed between the two voltages. With a properly synthesized v_i, the power exchanged between the converter and the AC grid across the reactor lf follows its reference.

In Figure 7, the current and the voltage in the natural abc frame are transformed in the synchronous dq frame, and a cascaded control is used. The control is composed of four blocks:

- Phase-Locked Loop (PLL): it observes the three phase voltage at the PCC located between the converter and the AC grid, and estimates its angle θ, as illustrated in Figure 8. This information will be used by the other blocks.

- Outer power loop: based on p_{ref} and q_{ref} , the reference values of active and reactive power, the outer power loop calculates the current references, denoted by i_L^{d*} and i_L^{q*}, which are then sent to the inner current loop. By aligning the grid voltage to the d axis, p and q can be decoupled and thus controlled independently. In particular, p depends only on i_L^d while q only on i_L^q. To calculate i_L^{d*} and i_L^{q*} based on p_{ref} and q_{ref} respectively, the control structure in Figure 7 uses a measurement of the PCC voltage to generate the current references, where p_{ref} and q_{ref} are simply divided by the grid voltage to obtain i_L^{d*} and i_L^{q*}. An alternative way to calculate the current references is to use closed-loop control, where PI controllers compare the power references with the measured and filtered power, and then adjusts the current references.

- Inner current loop: based on the current references i_L^{d*} and i_L^{q*} sent by the outer power loop, the inner current loop calculates v_i^{d*} and v_i^{q*}, the desired voltage to be synthesized by the converter, which are then sent to the PWM block. The PI controllers compare the current references with the measured currents, and then adjusts the voltage references. This inner loop is used to control the current flowing through the converter and limit potential over currents. More information about the tuning can be found in [46].

- Pulse-Width Modulation (PWM): based on the v_i^{d*} and v_i^{q*} given by the inner current loop, the PWM generates the gate control signals, which are sent to the switches of the 2-level VSC so that the fundamental component of the obtained voltage is the desire voltage. In case of the other types of VSC, such as Modular Multilevel Converters (MMC), adequate control should be implemented to synthesize the desired voltage [47].

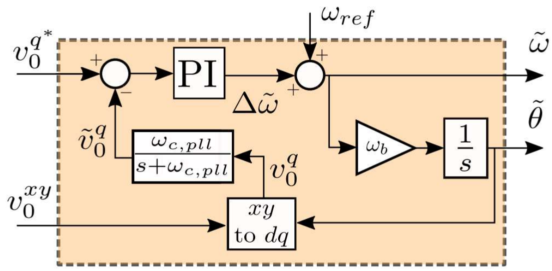


Fig. 8: Detailed control scheme of a classical PLL [48].

The grid-following control is not capable of feeding a passive network, because it always needs a grid voltage to follow, whose frequency and magnitude should be regulated by synchronous machines or converters working in other control modes. When left unregulated, the grid voltage and frequency may deteriorate and result in a voltage collapse, which is unacceptable from the demand-side point of view.

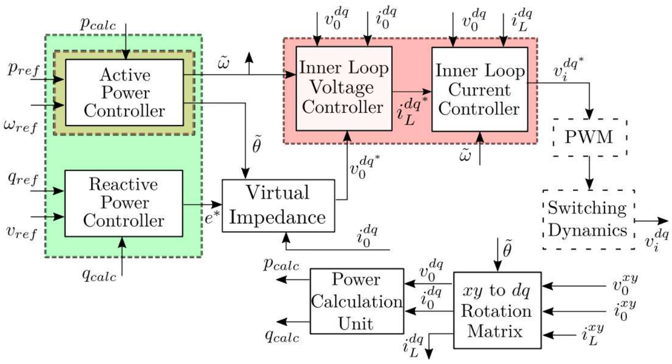


Fig. 9: VSC cascaded structure control scheme in voltage-source mode.

B. Voltage-source mode

This control mode, which is also referred to as grid-forming control, has emerged in islanded micro grids first [11]. In this mode, the VSC operates as a voltage source and, in consequence, generates a voltage of desired magnitude and frequency at the connecting bus.

The general scheme is given in Figure 9. The voltage at the PCC, denoted by v_0, is also the voltage of the capacitance c_f. This capacitance can be the physical capacitance of an LC filter [49] or the capacitance of an AC component such as an overhead line [50] if there is no filter. The control scheme is composed of the following blocks:

- Outer power loop: based on the voltage and current measurements at the PCC, the control loop calculates the active and reactive powers which are compared with the references. The control errors of active and reactive power are used to adjust, respectively, its frequency $\widetilde{\omega}$ and voltage magnitude e^*. This function reflects the principles of grid-forming which will be detailed in Section 3.C.

- Virtual impedance: when several VSCs are working in voltage-source mode in parallel, this block can be used to eliminate the circulating currents between them. In fact, it changes the voltage reference e^* sent by the outer power loop to emulate an additional impedance between the controlled voltage v_0 and the PCC to generate the voltage reference v_0^{dq*} which is used for the inner control loops, as described in [49].

- Inner control loops: In addition to the inner current, control similar to the one in Section 3. A for the grid-following control, there is also an inner voltage control law that controls v_0^{dq} using PI controllers and generates current references i_L^{d*} and i_L^{q*} for the current controller. More information about the tuning can be found in [51].

- Pulse-Width Modulation (PWM): similar to the one in Section 3.1.

There are in the literature different variants of grid-forming control, which depends on the way the power variations and the voltage references are coupled in the outer power loop. In particular, in Figure 10c, the droop-based grid-forming control [52], [53], [51], [54] couples the active power deviation with that of the VSC estimated frequency $\widetilde{\omega}$. The virtual inertia and load sharing of the grid-forming control can be tuned by acting on the low-pass filter cutoff frequency ω_{pq} and the droop gain $m_{p\omega}$ given in Figure 10c.

It is important to note that the vf control, also known as voltage and frequency control [21], which basically imposes a constant voltage magnitude e^*, usually 1 p.u., and a constant frequency $\widetilde{\omega} = \omega_{ref}$, usually 50 Hz or 60 Hz, may also be referred to as grid-forming control in micro grid literature [11]. In fact, vf mode can be seen as a particular case of the scheme given in Figure 9 where the outer loops are bypassed and the references are fixed values of e^* and $\widetilde{\omega}$.

C. Classification in the context of transmission grids

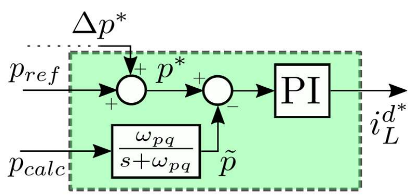
Thanks to the small size of a micro grid, a grid-forming converter is able to impose by itself the frequency to the whole system. However, in the context of a transmission grid, one single converter, which is of much smaller rating than the whole synchronous area, would become incapable of imposing the frequency on its own. Therefore, compared to its original definition in the micro grid where the converter behaves as a voltage source with imposed frequency and voltage magnitude, the grid-forming control in the transmission system is slightly different, and the following classification can be used instead:

- Grid-following: the converter works as a current source that injects power without consideration on the grid conditions.

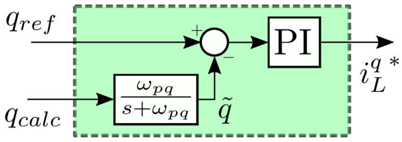
- Grid-supporting: the converter works as a current source and modulates its power references with respect to the initial load flow conditions to provide voltage, frequency or angle support. In other words, the grid-supporting combines the current-source working mode with an external control modulating the power references. A commonly-used method for controlling the active and reactive powers using a PI control is given in Figures 10a, 10b.

- Grid-forming: the converter works as a voltage source and provides voltage and frequency support. However, the frequency imposed by the converter will not be the nominal frequency, but such that the resulting power and the frequency are coupled to emulate the behavior of SM. The differences between existing grid-forming controls lie in the different control designs of their active and reactive outer power loop and the coupling between them. In addition to the droop-based control given in Figs. 10c 10d, other options exist, such as emulation of Synchronous Machines (SM) [55], [56], [57], [58], [59], [60] and more advanced control-oriented strategies [61], [62]. Besides, some comparisons were drawn between different grid-forming options in micro grids [63] and in transmission grids [64], [65] and showed similar small- signal behaviors and compatible control laws between each other. However, the transient stability analysis showed different behaviors of the grid-forming options [66].

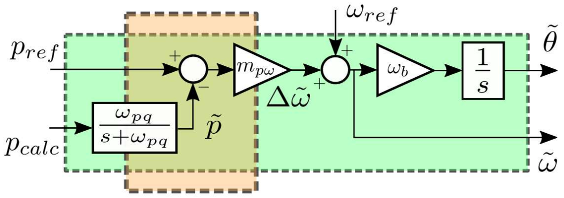
Note that the above classification, borrowed from [11], is somewhat an abuse of language, because the classification criterion is a mixture of the control method and control objective. On the one hand, in terms of the control method, the



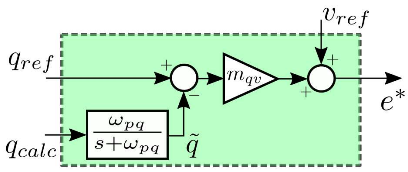
(a) Active power control loop with PI controller in current-source mode



(b) Reactive power control loop with PI controller in current-source mode



(c) Droop-based active power control loop in voltage-source mode



(d) Droop-based reactive power control loop in voltage-source mode

Fig. 10: Examples of the outer power control loops of the VSC in current and voltage source modes respectively.

grid-supporting control resembles the grid-following since both have the converter working as a current source; on the other hand, in terms of the control objective, the grid-support control seems closer to the grid-forming control, since both make the converter to contribute to the voltage and frequency regulation. In other words, to support the frequency, one can either use the grid-supporting control where a Δp^* term is added in the active power controller of the converter working as a current source, as described in Fig. 10a, or alternatively, use the grid-forming control as described in Figure 10c. In addition, the active power controller of the grid-forming scheme from Figure 9 plays a double role as described in Figure 10c. Indeed, it provides a PLL-free synchronizing unit [52] and makes the VSC contribute to frequency support as SGs do, i.e. by providing both synthetic inertia and primary frequency response [49].

In terms of performances, grid-following control is designed to ensure a good power tracking of the power references p_{ref} and q_{ref} using a dedicated controller as in Figures 10a, 10b. However, the behavior of the VSC relies on strong grid assumptions, i.e. with a high SCR and the VSC can even become unstable if connected to a weak grid (SCR<3). On the other hand, the grid-forming control has a power tracking capability thanks to its power controller shown in Figures 10c, 10d but since it behaves as a voltage source, its AC power response depends on the SCR. However, it is capable of working in weak grid conditions as well, on the contrary to grid-following controlled VSCs. These conclusions are shown in Fig. 11 where simulations were carried out using a simple benchmark containing a VSC model based on Figure 6 which is connected to an infinite bus through a transformer and a line modeled with a dynamic phasor model.

IV. Grid-Level Control Modes

With the current-source and voltage-source modes described at the converter level in Section 3, this section presents their services from a grid point of view.

A. Frequency support

Contrary to SGs whose frequency response is a combination of the physical behavior and explicit control, the VSC output power is entirely decoupled from the grid frequency behavior in grid-following mode. However, there are different active power profiles that can be provided by the VSC to support the grid frequency:

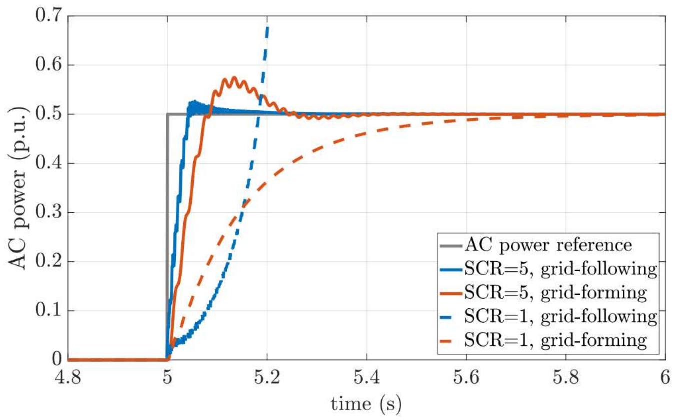


Fig. 11: Influence of the SCR on the performances of the VSC in terms of power tracking, following a 0.5 p.u. step of pref . The test-case is based on [67] with PLL gains taken from [68].

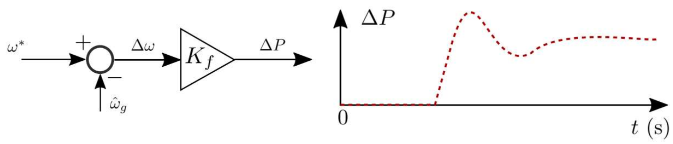
- Active power / frequency droop: developed in [69], [70], [71], [72], its aim is to provide an active power response that is proportional to the measured frequency deviation as described in Figure 12a. This control scheme is inspired by the primary frequency control of traditional SGs given in Fig. 1. In consequence, the VSC takes part in the load sharing with the SGs.

- Virtual inertia: as in [73], [74], with this control, almost instantaneously after the disturbance, the converter changes the active power reference proportionally to the RoCoF in order to emulate the kinetic energy delivered by the SG's rotor. It is known as the inertial response, and is illustrated in Figure 12b. It is important to note that the implementation of a derivative term $\frac{d\Delta\omega}{dt}$ would require an additional notch filter in practical conditions.

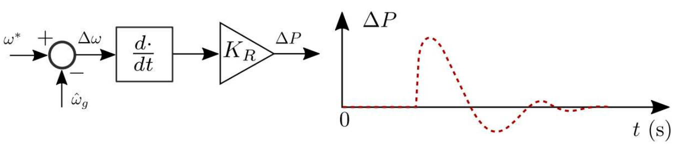
- Fast Frequency Response (FFR): this type of response has started to spread in islanded transmission grids [22] and provides an active power contribution deployed with a latency of less than 1s [75], [76], [77]. In consequence, it can be seen as a trade-off between the inertial response and the primary frequency control, and the power profile of the FFR can be customized instead of following a certain pattern, as illustrated in Figure 12c.

As to a grid-forming converter, it provides inherent frequency support since it emulates the SG dynamic response, i.e. with virtual inertia and load sharing capability. Concerning this last item, the current-source controlled and voltage-source controlled VSCs provide similar responses if sized and tuned accordingly [78]. However, if the DC-side of the converter is not adapted to provide this load sharing capability, this contribution may not be desired. This inherent frequency droop action of the grid-forming controller can thus be cancelled by using a high-pass filter or a frequency estimation $\tilde{\omega}$ from a PLL [79] instead of the nominal frequency ω_{ref} in the active power control loop given in Figure 10c. Another option is to replace the droop gain $m_{p\omega}$ by an IP controller [80].

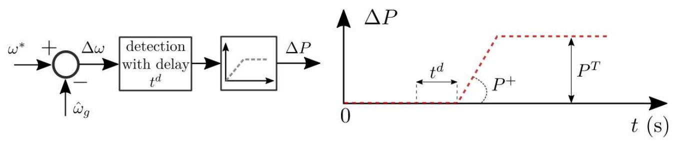
About the inertia then, since the grid-forming controlled VSC is operated as a SG during the first instants following any kind of disturbances, it does provide some inertia to the grid. On the other hand, the inertia provided by the virtual inertia controller in current source mode from Fig. 12b is slightly different because it is an extra control loop that relies on the PLL speed, accuracy and the notch filter to deliver such inertia, meaning it will not be delivered at the very first instants following the disturbance.



(a) Active power / frequency droop response



(b) Virtual inertia response



(c) Fast Frequency Response (FFR)

Fig. 12: Illustration of different potential supporting actions using a variation of power reference provided by a power converter.

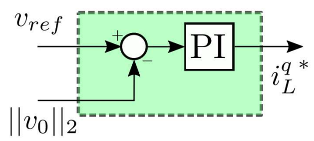
B. Reactive Power Support

PE-based systems have been used for decades to provide AC voltage / reactive power support. One of the most famous examples are STATCOM systems [81], which are also based on VSC technology. Indeed, by controlling the reactive current of a converter, whether it is an HVDC grid, a FACTS or a system connected to an energy source, the VSC is capable of adjusting its reactive power to support the PCC voltage as described in Section 2.2. In the literature, there are different ways the VSC can control its reactive power to support the AC voltage. In addition to the reactive power loop from Figure 10b, there are other options which are given in Figure 13. In Figure 13a, another implementation of the reactive power loop is proposed to control the PCC bus voltage using PI control. In Figure 13b, the support is a power droop similar to the active power frequency droop in Figure 12a, which is used to provide a support proportional to the voltage magnitude deviation. In Figure 13c, the controller regulates the voltage magnitude at the PCC but the reference is changed dynamically with respects to the reactive power deviation. However, the two implementations from Figures 13a, 13c can be a problem if multiple VSCs with this type of control are connected to the same bus because the PI controllers will compete against each other, creating undesired oscillations.

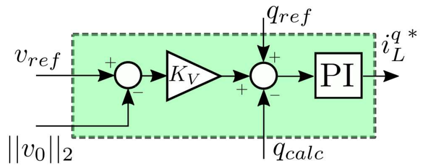
For the grid-forming control, the behavior of the VSC is based on controlling the PCC voltage magnitude as shown earlier in Fig. 10d. However, as for the options given in Figures 13a, 13c, there is a problem if multiple converters are connected in parallel at the same bus. In practice, this is one of the advantages of implementing a virtual impedance as in Figure 9. Also, it is important to note that the grid-forming control is not only about maintaining the AC voltage magnitude but also its phase, as it is described in the next section.

C. Contribution to system strength

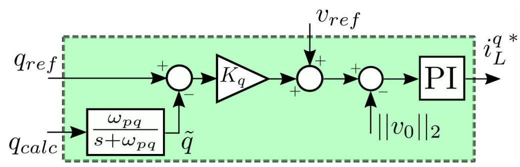
In the literature, it has been shown that PE-based converters controlled in current-source mode can be unstable when connected to a weak grid, i.e. where the SCR at the PCC is inferior to 3, due to the interactions between the line dynamics and the PLL [83]. To illustrate these interactions, a frequency analysis of the open-loop PLL given in Figure 8 is performed for different PLL gains. The analysis is carried out considering $k^{\alpha}_{p,pll} = \alpha.k_{p,pll}$ and $k^{\alpha}_{i,pll} = \alpha.k_{i,pll}$ for different values of α = {1, 2, 3... 20}, where $k_{p,pll} = -0.05\ p.u.$, $k_{i,pll} = -2.53\ p.u.$ and $\omega_{c,pll} = 200 rad/sec$, based on values from [68].



(a) AC voltage magnitude control [82].



(b) AC voltage droop control [11].



(c) AC voltage magnitude control with reactive power droop [72].

Fig. 13: Different implementations of AC voltage support using reactive power modulation in current-source mode.

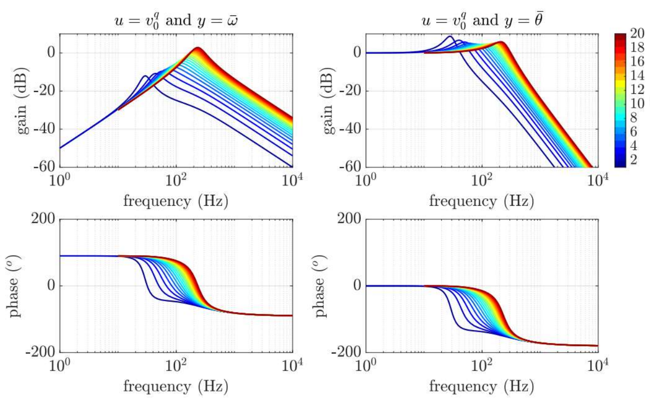


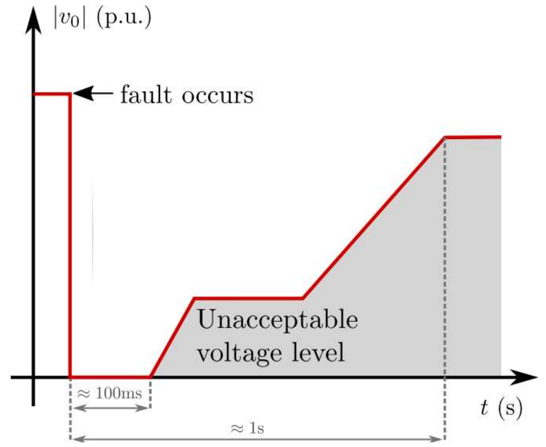
Fig. 14: Bode plots of the linearized PLL for different values of gain $k^{\alpha}_{p,pll}$ and $k^{\alpha}_{i,pll}$ with respect to the two outputs $\overline{\omega}$ (left-side) and $\overline{\theta}$ (right-side).

As shown in the Bode plots given in Figure 14, there is a trade-off between the speed of the tracking capability of the PLL and its robustness: if the PLL is fast enough to track any frequency changes, it is also more sensitive to disturbances. The resonance frequency of the PLL is found to be around 100 Hz, which is the order of magnitude of the transmission line dynamics [29], hence the negative interactions with the lines causing instability when the lines are too long, which correspond to weak grid conditions.

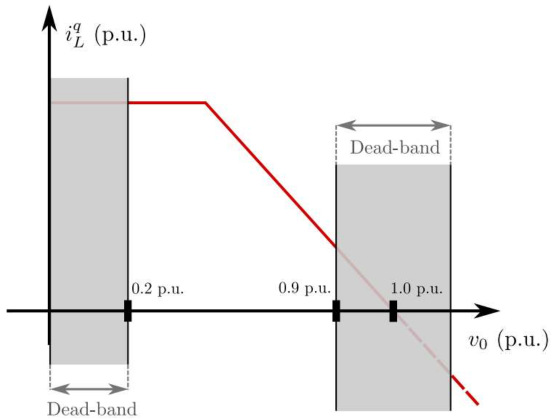
Nowadays, this weak grid issue is responsible for renewable energy curtailments in some power systems [84]. In the literature, there are three main solutions to allow more VSCs to be connected to weak grids:

- Introduce synchronous condensers to provide system strength to the weak regions [85]. However, this solution does not include any VSC-related function;

- Reinforce the weak grids, for example by grid-forming control in Figure 9. This is different from the services by FACTS that improve the long-term voltage stability by reactive power compensation [15]. However, it is possible to control STATCOMs using grid-forming control [86] to make them contribute to the system strength;



(a) Typical Low Voltage Fault-Ride-Through (LVFRT) profile imposed by a grid operator.



(b) Reactive fault current requirements depending on the voltage level. Based on [39] and [90].

Fig. 15: Synthesis of the expected voltage and current responses of a VSC following an AC-side fault.

- Develop novel PLL algorithms for weak and very weak grids, i.e. with a SCR ≤ 2 [68], [87] and keep the current-source control structure presented in Figure 7. Today, this current-source control has better performances than classical voltage-source controls in terms of power tracking for strong grid situations [88], [67], as illustrated in Figure 11. Therefore, the VSC owners and TSOs should reach an agreement on whether most, if not all, of the VSC should participate to some extent in this voltage control, as the SG used to do, or only some specific VSC should be required to ensure minimum service in this aspect.

Even though the notion of SCR was a consistent metric for short-circuit contributions and voltage stiffness in SG-based systems, it is not sufficient enough in PE-dominated systems since the fault-transient behavior and the system strength in normal operation are no longer coupled. Developing novel metrics to assess the system strength levels in PE-dominated grids is still an open-topic. Indeed, contrary to SGs, a VSC in grid forming does not maintain its voltage-source behavior at all time because of its limited overcurrent capability. Indeed, its contribution to the voltage stiffness strongly depends on the nature of the disturbance and its operating point, in particular its active and reactive power references. In that way, dynamic analysis are required to assess the voltage stiffness of a PE-dominated grid, while it was possible for SG-dominated grids to use only static analysis [85].

D. Short-circuit contributions

Unlike SGs whose high overcurrent capability makes it possible to contribute to short-circuits during AC faults, as described in Section 2.4, VSCs are highly sensitive to over currents due to their semiconductor devices. If no current limit is imposed, the conversion valves will be blocked and the VSC will be disconnected from the grid, hence interrupting its power conversion and making it unable to contribute to the short-circuit currents.

In consequence, we may require in the future that VSCs have a Fault-Ride through (FRT) capability where they remain connected when encountering large disturbances, such as a fault or a generation unit loss. The FRT capability is usually assessed by TSOs using a FRT profile which corresponds to the minimum voltage response of the equipment following a given fault to remain connected to the grid. There are many profiles which depend on the TSO grid codes [89]. A typical FRT is given in Fig. 15a. In addition to the voltage deviations, the VSC can still lose synchronism even though the voltage magnitude remains within the FRT profile. This transient stability needs to be assessed and is currently a topic of great concern by academia [90, 91].

Second, in addition to remaining connected, the VSC may also be asked to contribute to the short- circuit currents in order to help detecting the fault. In the literature, there have been some studies about developing strategies to make the VSCs in current-source mode remain connected and provide 1 p.u. of reactive current when the voltage drops below a certain level [92], [93], 90% of nominal voltage in [90]. However, in several grid codes, these contributions are not mandatory anymore if the PCC voltage, v0 in Fig. 15b, drops below 20% of its nominal value [39] as it is illustrated in Fig. 15b.

In the voltage-source mode, as in Figure 9, the FRT capability is more complex to achieve, because the branch current results directly from the voltage the VSC imposes at its terminal. In consequence, the VSC control must act quickly to avoid a fault current which would damage the conversion devices or force the interruption [45]. In the recent literature, two main ways of achieving FRT with a VSC controlled in voltage-source mode have emerged:

- Use of a backup PLL: When the control detects a current rise, it switches to an emergency current- source mode and keeps the synchronization through a backup PLL. The new power references are chosen in order to inject a fault current of 1 p.u. [52].

- Limitation of the voltage magnitude: The control keeps running in voltage source mode but the voltage reference is decreased to limit the branch current. One solution could be the implementation of a fault detector with a virtual impedance control as in [94], [95].

For both the current-source mode and the voltage-source mode, the short-circuit contribution of a VSC is physically limited by the semiconductor devices. In consequence, the current way the TSOs detect and clear AC faults has to be re-defined for large penetration of PE-based sources scenario [45]. There are two tendencies that have emerged in the literature for AC fault detection:

- Enhance the fault response of PE-based sources: According to this conservative strategy based on the assumption that power grids will still rely on SGs, the fault detection algorithms are unlikely to change. On the other hand, the very limited overcurrent capability of VSCs, currently at approximately 110% as shown in Table 2, must be enhanced. One solution is to upgrade the thermal management system of the converter. There are examples in the literature of PE-based systems where the current is able to go up to 200% for less than 200µs [92]. Another solution is to integrate synchronous condensers in parallel with the VSC to enhance the fault response at the point of coupling [96].

- Change the AC grid fault detection strategy: Today the AC fault detection algorithm is based on differential functions, relying only on measurements of currents and Kirshoff's current law. However, with the recent advances in system identifications, new methods based on Dynamic State Estimation (DSE) make it possible to monitor a given protection zone without requiring large over currents or coordination between the zones [97].

However, the choice of relevant solutions requires the coordination of the different actors (TSOs, converter manufacturers, etc.) and is more a design problem rather than a control problem.

E. Power oscillation damping

Following the development of several embedded HVDC links in some interconnected systems, several studies have shown that VSC-interfaced power sources and VSC-HVDC links operating in current-source mode can provide a Power Oscillation Damping (POD) function if the active power reference are adjusted accordingly [98], [99], [100], and [101]. These power references can be changed according to the difference of the two-area frequencies $\Delta p^* = f(\omega_2 - \omega_1)$ or the difference between the reference and the local frequency $\Delta p^* = f(\omega^* - \omega_2)$ for instance, as illustrated in Figure 17a.

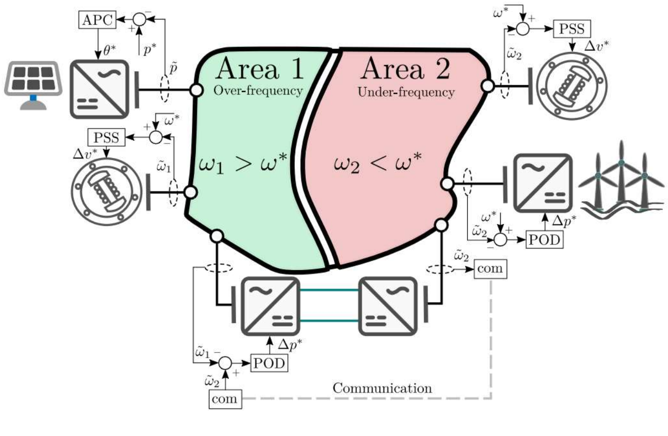
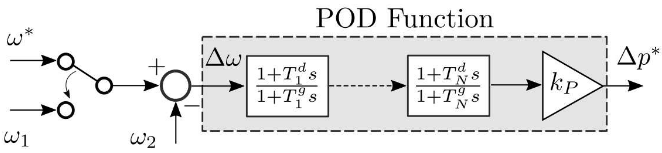


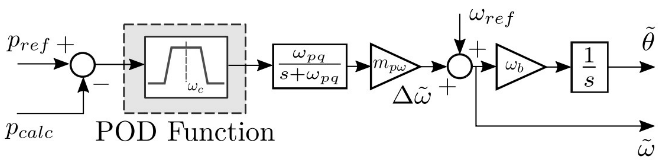
Fig. 16: Different manners of damping inter-area power oscillations in a single synchronized power system using synchronous generators, VSC-interfaced power sources and VSC-HVDC links.

In the former case, the system needs communication devices whereas the latter option only relies on local measurements. Both cases are illustrated in Figure 16. The POD function can also be achieved using reactive power reference modulation [102] or be applied to Multi-terminal HVDC (MTDC) embedded systems [103].

For grid-forming VSCs, also given in Fig. 16, since they have a SG-like behavior, they add supplementary electromechanical-like modes in the system. However, these modes can still be damped by adding an additional damping controller though. In this case, to damp the power oscillations, the power references p_{ref} and q_{ref}, defined in Figure 9, can be adjusted similar to a VSC working in current-source mode. In this way, the power-tracking capability of the grid-forming mode [67] is used to provide POD. Another option is to adapt the active power control loop to add a notch filter which eliminates the undesirable oscillations, as in [104, 105] and illustrated in Figure 17b.



(a) POD control structure using active power modulation [100].



(b) POD control structure using modified droop-based grid-forming control [104].

Fig. 17: Options for POD functions depending on the VSC control mode.

Nevertheless, all these types of POD impose some constraints on the VSC:

- Some power headroom must be dedicated to POD at all time to be capable of acting on the power references. In consequence, the VSC cannot operate at its maximum apparent power.

- It impacts the transferred power of the VSC, which can generate market-related and operational issues if the HVDC system is between two distinct areas/countries.

V. DISCUSSIONS & CONCLUSIONS

The two VSC control modes, namely, the current-source control and the voltage-source control, were presented in Section 3, while the converter services to the grid were discussed in Section 4. As described in this last section, most of the grid support functions can be added to the grid-following scheme by slightly modifying the control, i.e. by adding current limitations or $\Delta p^*/\Delta q^*$ power references. As a consequence, the supporting action can be tuned accordingly to the available reserves from the DC side. On the other hand, voltage-source mode can provide most of the grid services since it is capable of emulating SG behavior. However, because of its voltage source behavior, the extracted power is a consequence of the imposed volt- age. Thus, it requires a large energy source to provide functions such as frequency support, system strength contribution or POD. The short-circuit contribution is however limited by the semiconductor device over- currents. Traditional SGs can provide the short circuit current thanks to their large over current capability, as shown in Section 2. These functions are included in the definition of grid-forming in some references [27] though, which can be misleading from a control point of view. To be properly integrated in the grid, the VSC control must consider the energy management algorithms of the power sources on the DC side that deliver this supplementary energy, which could be brought directly in DC or through another AC/DC converter. This extra energy can be provided by deloading PV arrays [75], wind power plants [106, 107, 108] or by storing it in an Energy Storage System (ESS) through Li/ion batteries [78, 109] or supercapacitors [110]. On the other hand, it is possible to control a VSC in grid-forming even though there is no dedicated storage unit, as for HVDC links interfacing two AC grids [111] or interconnecting offshore wind farms [112]. As a summary, the compatibility of the two control modes with the grid services is given in Table 3, where frequency support is split into virtual inertia and load sharing capability to highlight this.

This distinction between the different objectives of a grid-forming controlled VSC are an up-to-date topic. In [113], several categories of "grid-forming" were drawn such as:

- grid-forming: refers to VSCs controlled as constant voltage sources, which is equivalent to the vf control described in Section 3.2;
- synchronous grid-forming: refers to VSCs in grid-forming which are capable of synchronizing with other parallel-connected voltage sources (grid-forming VSCs, SGs or SCs);
- Virtual Synchronous Machine (VSM): refers to synchronous grid-forming VSCs which are capable of providing power from an extra source of energy and a short-circuit current during faults.

In this classification, grid-forming and synchronous grid-forming refer to control aspects: the VSC is seen as a voltage source from the grid perspective and the outer loop control inputs are a voltage magnitude and angle, as in Fig. 9. On the other hand, Virtual Synchronous Machine refers to the grid aspects because it includes some of the support functions described in Section 2. This terminology is compatible with Table 3 and shows the need to distinguish in the "grid-forming" related literature the control aspects which makes it possible to have a PLL-free synchronization from the grid aspects which replaces the functions of the SGs with VSCs. This understanding makes us realize that some inherent functions of SGs, such as inertia, whose shortage in future power systems was considered as the worst issue for European TSOs in 2017 [43], are less important than others, such as system strength reinforcement. In fact, it is clear now that weak grids is a significant challenge right now for islanded power systems such as Texas [84] or Australia [114] where weak grid issues were recently reported. In conclusion, the desired behavior of VSCs in the future might not be to emulate SGs but could be less restrictive since those PE-based sources are much more controllable.

The contributions of this article can be listed as follows:

- A comprehensive introduction to the upcoming challenges of AC transmission grids due to the increasing amount of renewables and the ongoing dismantlement of synchronous generators;
- An overview of the main VSC control modes and a front-

Table. III

COMPATIBILITY OF THE TWO MAIN VSC CONTROL MODES WITH THE DIFFERENT GRID SUPPORT FUNCTIONS

	Current-source mode		Voltage-source mode (Grid forming)	
	Grid-Following	Grid-Supporting	with extra energy.	w/o extra energy.
Converter-level				
synchronization	Uses an external PLL to capture the grid frequency and phase angle.		Observes the variations of active power to estimate the grid frequency and phase angle. The converter and the grid are naturally coupled by the synchronizing torque.	
power-tracking	Relies on strong grid assumptions. Quite good performances in power tracking when these conditions are met. See Fig. 11.		Not as good as current-source mode for power tracking in terms of both time re sponse and static error [88],[67]	
current-limiting action	Current limiters can be implemented in the current controller.		No inherent current controller at first place. But cascaded structure with current controller is now widely used [51],[49].	
Grid-level				
virtual inertia	No. The VSC tracks power references.	Possible with virtual inertia control as in Fig. 12b. Not as well adapted as grid forming option [74].	Yes, due to the dynamics of the Low-Pass Filter (LPF) in the active power controller shown in Fig. 10c.	Yes, due to the LPF dynamics. Support is however limited by the quantity of available DC power.
load sharing capability	No. The VSC tracks power references.	Possible with active power / frequency droop control as in Figure 12a.	Yes, as shown in [51], [64].	Impossible if there is no dedicated storage system [112].
reactive power support	No. The VSC tracks power references.	Possible with the supporting actions described in Fig. 13	Yes, the VSC controls the PCC volt age magnitude and adjusts its reactive power accordingly as long as it respects its overcurrent limitations.	
system strength contribution	Impossible. The VSC is operated as a current-source and the PCC voltage is seen as an external disturbance.		Yes. The VSC is operated as a voltage source and the PCC voltage magnitude and phase angle are seen as control variables [11].	
short-circuit contribution	Can be implemented as in [25]. The contribution is limited by the thermal limits [45].		FRT must be taken care of because of the voltage source behavior. See [52] or [94], [95] for control options.	
power oscillation damping	No. The VSC tracks power references.	Possible using active or reactive power reference modulation as described in Fig. 17a. See [98], [99],[100], and [101].	Inherent damping based on SG emulation but can disturb the system as well. Compatible with SG's PSS.	POD actions can be added as in Figs. 17a ([98],[99], [100], [101]) - 17b ([104]). Needs some available energy for active power damping.

to-front comparison of the current-source and voltage-source modes, respectively the grid-following and grid-forming controls;

- A presentation of the main ancillary services that used to be realized by SGs and how the two types of VSC control modes can be adjusted and modified to provide some of these functions to the grid.

In future work, it should be primordial to investigate the compatibility of all the controllers with each other and how to dispatch the different control modes within a given grid.

Acknowledgments

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