Grid-Listening and Grid-Ringing: Alternative Concepts for Grid-Following and Grid-Forming within Power Systems Frequency Transients

Salvatore Favuzza
University of Palermo
Palermo, Italy
salvatore.favuzza@unipa.it

Rossano Musca
University of Palermo
Palermo, Italy
rossano.musca@unipa.it

***Abstract*—The paper introduces the concepts of grid-listening and grid-ringing as alternative ways to interpret the classes of converter control commonly known as grid-following and grid-forming. The intrinsic nature of these two controls define their interaction within the frequency transients in power systems, and in particular with the disturbance propagation and the synchronization process. The grid-following interacts with the oscillations in the system just detecting them: for that, it can be regarded as grid-listening. The grid-forming interacts with the power-frequency oscillations contributing to them: for that, it can be regarded as grid-ringing. This conceptual revisiting is illustrated with a representative system, and further discussed with some examples on a benchmark power system.**

***Index Terms*—frequency transient, grid-following, grid-forming, oscillations, power systems dynamics, synchronization.**

I. Introduction

The energy transition and the continuous integration of renewable energy sources are pushing towards power systems operated with high percentages of non-synchronous generation. The power converters interfacing the generation sources to the system have received a significant attention, especially with respect to the characteristics of the controls and the impact on the power system. The control structures of converters have been categorized into two main concepts, the grid-following and the grid-forming. These two control classes have fundamental differences, but they can be also united by some similarities. A duality of the two concepts can be recognized [1] [2], and it is convenient as well as suggestive to define one in relation with the other. The majority of power converters implements standard and well established vector control methods, which are designed to inject a given current into the grid and for that, synchronize with the grid through the dedicated unit called phase-locked loop (PLL). In this case, the converter follows the frequency variation at the interconnection with the grid, determining the synchronizing angle through a voltage-based mechanism. Grid-following converters usually do not participate in the frequency control of the system: this can however be achieved in different ways [3]–[10], extending the active power control loop with outer blocks and additional features. As an example, a possible solution is the combination of a derivative control for the provision of synthetic inertia and of a droop control on frequency deviation for the provision of primary frequency reserve. An emerging and promising alternative to the standard vector control of power converters is represented by the category of grid-forming controls. These controls are designed to provide a given voltage at the terminal and for that, synchronize with the grid autonomously through a dedicated unit. In this case, the converter forms the frequency variation at the interconnection with the grid, determining the synchronizing angle through a power-based mechanism. Grid-forming converters can inherently participate in the frequency control of the system, and they have been explored in the last years considering several different schemes and variations [11]–[18]. As an example, a common control scheme is the virtual synchronous machine, which is basically a swing-based control emulating the typical dynamics of a synchronous machine for the power-based synchronization with the grid. Another common grid-forming scheme is the power-synchronization control, which is also based on the emulation of the synchronizing mechanism of synchronous machines, but without including the inertial effect. Several scientific works focus on a comparative assessment of grid-following and grid-forming control schemes [19]–[23].

In this context, the paper contributes with a conceptual revisiting of the two main control categories, taking the perspective of frequency transients in power systems. From this perspective, the sources controlled either as grid-following or grid-forming can be regarded as elements sensitive to the power-frequency oscillations in the system. The intrinsic characteristics of these two controls define their interaction with the power system, and in particular with the disturbance propagation and the synchronization process, both transient phenomena taking place after a contingency in the system. The concepts of grid-listening and grid-ringing are presented with a representative system, and further discussed with some examples referring to a standard benchmark system. The discussion provides a deeper understanding about the frequency dynamics of power systems with grid-following and grid-forming converters, demonstrating an alternative way of regarding these two control concepts.

II. Grid-Listening and Grid-Ringing

All the elements connected to the power system are sensitive to the oscillations experienced by the frequency during transient conditions. The sources with the predominant impact and interaction have been traditionally the synchronous machines of power plants. It is then convenient to start the presentation of the concepts referring to them.

At the occurrence of a contingency in the system, like f.i. a power imbalance or a topological change, the synchronous machines will synchronize with each other exchanging power through the interconnecting transmission system. During this transient process, the disturbance propagates within the system through the oscillation couplings, interpreted as a succession of mutual interactions [24]. The information about the changed status of the system is ultimately carried out by the frequency itself: this information is physically exchanged between the synchronous machines through the natural way of communication represented by the power system itself [25]. Assuming the network to be reduced only to the source nodes, the swinging behaviour of the generic machine i can be described by:

$$M_i\ddot{\delta}_i + D_i\dot{\delta}_i = \tau_i - \sum_{j=1}^{n} p_{ij} \tag{1}$$

$$p_{ij} = k_{ij}\sin(\delta_i - \delta_j) \tag{2}$$

where M_i, D_i and δ_i are respectively inertia coefficient, damping coefficient and angle of the machine; τ_i represents the mechanical power, while the sum represents the active power output of the machine, expressed as sum of the interactions with the other generators. The coefficients k_{ij} are given by $k_{ij} = V_iV_jY_{ij}$. For sake of simplicity, the admittances are assumed to be purely imaginary. In a spring analogy, the synchronous machines represent the coupled oscillating sources, and the coefficients k_{ij} are the spring constants, and p_{ij} are the elastic restoring forces which establish the synchronism in the system [26] [27]. Equations (1) and (2) can be used to describe the transient phenomenon of disturbance propagation in a power system under the form of propagation of electromechanical waves [28]–[30]. Under certain assumptions [31], it is possible to develop a a continuum swing model and derive the following expressions:

$$\frac{\partial \omega}{\partial t} = \frac{\omega_s}{2h}\left(p_g - \frac{\partial p}{\partial x}\right) \tag{3}$$

$$\frac{\partial p}{\partial t} = -E^2 b \frac{\partial \omega}{\partial x} \tag{4}$$

where h is the inertia constant per unit length, b is the susceptance per unit length, ω_s is the nominal system frequency, and E is the voltage magnitude, assumed constant in space and time. Equations 3 and 4 are formally similar to the telegrapher's equations, which describe the propagation of electromagnetic waves on a transmission line: in the case of electromechanical waves, the power P plays the role of line current, and the frequency f plays the role of voltage [32].

The integration of non-synchronous generation, controlled either as grid-following or grid-forming, is expected to determine a substantial change of the oscillation couplings in the system. The non-synchronous sources can be located between synchronous sources, along the interconnections which will perform as coupling for the oscillations. This situation is depicted in Fig. 1. When a contingency occurs on side A,

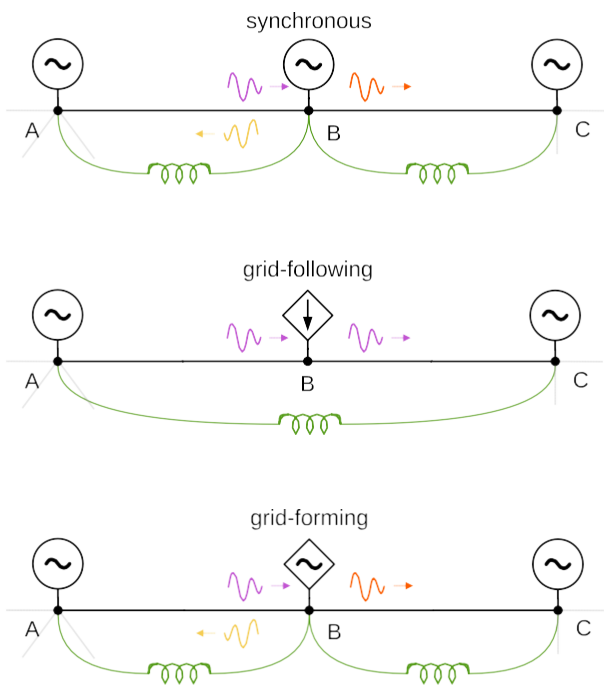

Fig. 1. Oscillation couplings and disturbance propagation.

the disturbance propagates towards B and C. If a synchronous machine is connected to B, the machine reacts to the arrival of the information carried by the frequency, interacting back with the source in A and transmitting a renewed information about the disturbance towards the source in C. If a grid-following converter is instead connected to B, the converter will just detect the arrival of the disturbance, and it will let the information pass unmodified towards the source in C. In this sense, the converter is just listening to the grid oscillations, without altering the propagation of the information carried by the frequency. If a grid-forming converter is connected to B, the converter will respond to the arrival of the information about the disturbance, interacting back with the source in A and sending a renewed information towards the source in C. In this sense, the converter makes the grid oscillations ringing, participating in the propagation of the information carried by the frequency. Even if not physically rotating like synchronous machines, grid-forming converters are ultimately oscillating elements, as they independently change their frequency during synchronization with the grid. It is important to remark that these considerations are generally valid for grid-forming control with inertial functionalities.

These considerations have a particular impact on the system in terms of the oscillatory behaviour after a contingency.

While grid-following sources do not participate in the elastic restoring forces for the synchronism of the system, making the synchronous machines electrically more distant from each other, grid-forming sources constitute with synchronous machines a set of coupled oscillators, interacting with each other to establish a coherent behaviour and thus achieve the synchronism. Therefore, the integration of grid-following converters leads to a greater separation between the elements that interact for synchronism, weakening the oscillation couplings between them. But at the same time, grid-following sources do not slow down the synchronization process, which can be achieved with a smaller amount of oscillations. The integration of grid-forming converters, instead, offers the possibility of reducing the electrical distances between the oscillating elements in the system, strengthening the oscillation couplings and thus supporting the synchronization process between the different parts. At the same time, grid-forming sources with inertial capabilities slow down the synchronization process, which will be achieved with a larger amount of oscillations.

III. Representative System

The concepts of grid-listening and grid-ringing can be demonstrated with the help of a simple yet representative system. The single line diagram of the network is shown in Fig. 2. This can be the situation of two synchronous areas, here represented as equivalents, where non-synchronous generation sources are integrated along the interconnection between the areas. Each area includes an equivalent synchronous machine and the primary controllers for voltage and frequency regulation. The non-synchronous sources can be controlled either as grid-following or as grid-forming. Two possible configurations are considered: only one non-synchronous source operating in the system (point P in Fig. 2), and all three non-synchronous sources connected along the transmission line between the two areas. In all cases, it is assumed that the non-synchronous sources do not provide any frequency reserve to the system. The dynamic data of synchronous machines and controllers

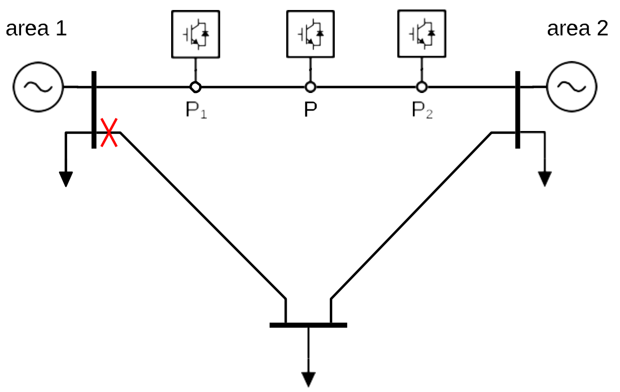

Fig. 2. Representative 3-bus 2-area system.

are adapted from [33]. The system is modelled for positive-sequence simulations in a commercial software, considering a sudden topological change with the opening of an interconnection between the two synchronous areas. The model with all the data for simulation is available at [34]. The results of the simulations are reported in Fig. 3. The first observation is that the integration of a grid-following source determines basically the identical transient behaviour of the basic case with no sources (see Fig. 3a and Fig. 3b). This indicates that the grid-following source does not alter the oscillation coupling between the two areas, being transparent to the passage of the disturbance and just listening to the information carried by the frequency. The integration of a grid-forming source, instead, reduces the difference between the frequencies of the two areas, facilitating the exchange of transient support between them, and also producing more oscillations in the system (see Fig. 3a and Fig. 3c). This indicates that the grid-forming source modifies the oscillation coupling between the two areas, ringing the information carried by the frequency back and forth towards the interconnected areas. A relevant observation concerns the grid-following with synthetic inertia: in this case, the converter provides a certain amount of inertial response, but the underlying mechanism for the realization of this functionality does not affect the oscillation couplings and the disturbance propagation in the system (see Fig. 3b and Fig. 3d). The results in case of multiple grid-following sources confirm the listening nature of this control concept, showing the same frequency transient of the basic case with no sources (see Fig. 3a and Fig. 3e). Conversely, the results in case of multiple grid-forming sources confirm the ringing nature of this control concept, showing the increase of mutual oscillations in the frequency transient of the system (see Fig. 3c and Fig. 3f). The case of multiple grid-following with synthetic inertia basically confirms the observation made for the case a single non-synchronous source (see Fig. 3d and Fig. 3g).

IV. Benchmark System

The concepts of grid-listening and grid-ringing are further discussed with an example on a standard benchmark system. The benchmark is a 39-bus system with 10 generator, also known as New England test system. The 39-bus system has been extensively used in several scientific works for the analysis of the oscillatory dynamics in power systems, and the complete set of data is available [35]. The system can be divided in two parts: an inner area, which models in detail the New England power system, and an equivalent, which models the remaining part of the bulk system. The system has an inter-area mode involving two machines of the inner area against the equivalent machine representing the bulk system. The 39-bus system is here considered as an example, and properly modified to the purposes of the study: all synchronous machines of the inner area are replaced with non-synchronous generation, except for the two machines involved in the inter-area oscillation with the bulk system. The system is simulated for a sudden power imbalance in the inner area. The results of the simulations are shown in Fig. 4.

The basic case considers the benchmark system unmodified, with all synchronous generation. In this case, a particular dynamic response to the disturbance can be observed,

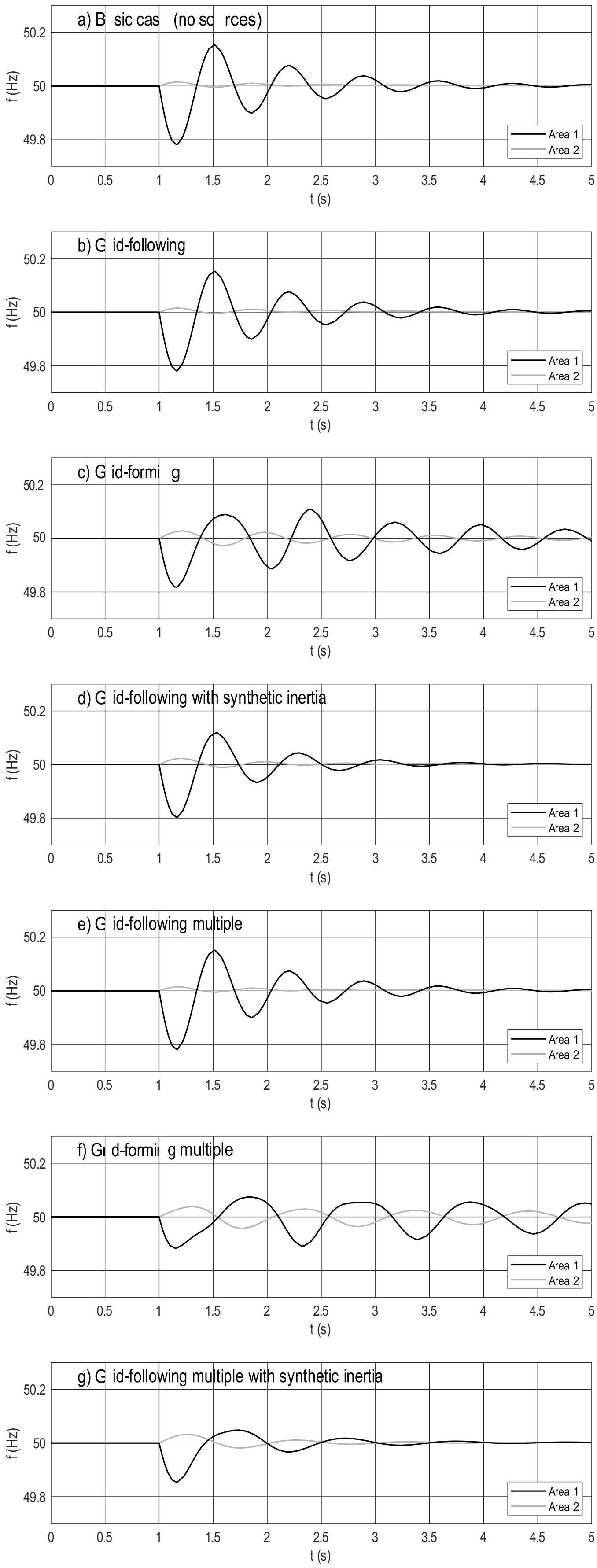

Fig. 3. Simulation results for a topological change in the system.

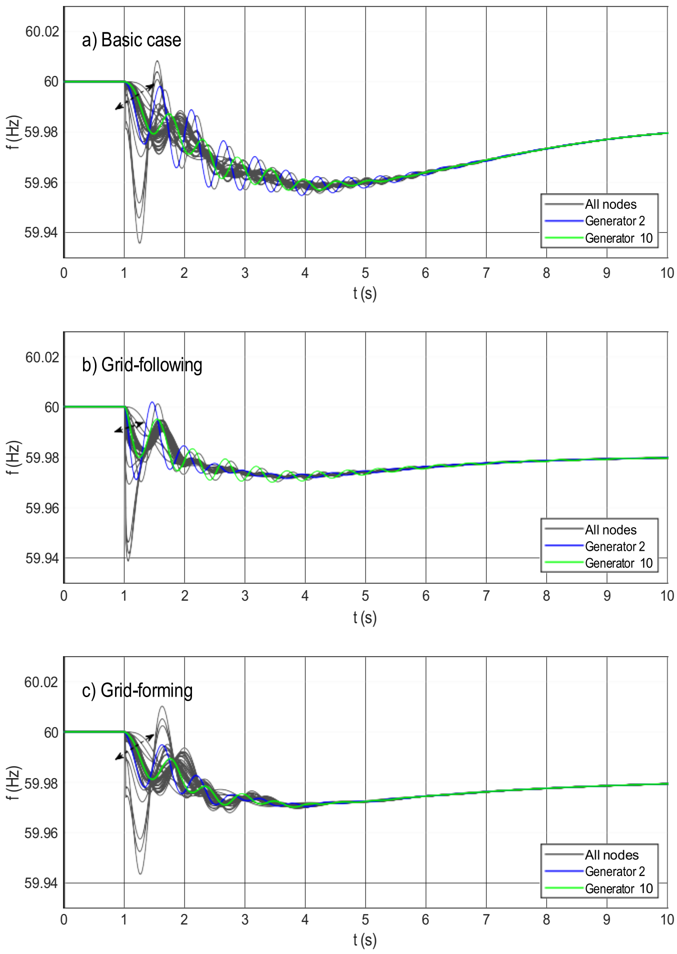

Fig. 4. Simulation results for benchmark 2.

characterized by several oscillations (Fig. 4a). When grid-following generation substitutes synchronous generation, the frequencies are located in a narrow band, denoting a lesser transient support exchanged by the sources and more severe local transients (Fig. 4b). The results confirm then that the oscillation couplings between the sources are weakened by the presence of grid-following converters, since they just listen to the power-frequency waves propagating in the system after the contingency. When grid-forming generation is integrated in the system as replacement of synchronous generation, the frequencies of the different parts spread again across a wide band, denoting a greater transient support exchanged by the sources (Fig. 4c). Conversely to the basic case of all synchronous generation, the frequency dynamics of the system with grid-forming converters is closer to a second-order dynamic response. The results of the example confirm that the oscillation couplings between the sources are strengthened by the presence of grid-forming converters, since they ring in reaction to the power-frequency waves propagating in the system.

V. Conclusion

Taking the perspective of frequency transients in power systems, the concepts of grid-following and grid-forming control for power converters can be revisited for an alternative and deeper insight of their integration in the system. When the system is affected by a contingency like a power imbalance or a topological change, the synchronization process takes place in the form of a propagation of power-frequency waves across the system. Sources controlled either as grid-following or grid-forming are elements sensitive to these oscillations: the particular reaction to them has been used to present the two alternative concepts of grid-listening and grid-ringing. Grid-following converters are regarded as grid-listening, since they just detect the information carried by the frequency, without producing any alteration of it. In this sense, grid-following converters are just listening to the grid oscillations. Grid-forming converters are instead regarded as grid-ringing, since they react to the information carried by the frequency, participating actively to the propagation of power-frequency waves. In this sense, the grid-forming converters make the grid oscillations ringing.

The work presented in the paper contributes with an advancement of the state-of-the-art, providing an alternative interpretation of the power converters controls from the system perspective. This interpretation of the concepts of grid-following and grid-forming opens the possibility for a revisited formulation of these control structures. This alternative understanding can lead to different potential applications, from the development of novel control schemes for power converters, to the design of operation and control of power systems with high percentages of non-synchronous generation sources, having the improvement of the power system dynamics as main drive of the activity.

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