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Wide-Synchronization Control for Power Systems with Grid-Forming Converters

Rossano Musca, *Senior Member, IEEE*, Eleonora Riva Sanseverino, Gaetano Zizzo, *Senior Member, IEEE*, Giorgio Giannuzzi, Cosimo Pisani

***Abstract*—The article presents a novel wide-area control for power systems with grid-forming converters. The concept of the proposed wide-synchronization control is first introduced, and a theoretical proof is offered. A simple yet effective methodology for the tuning of the control is also derived. The concept of wide-synchronization control is then applied to the actual case of the European power system, taken into examination with an appropriate large-scale dynamic model. The results of the analysis indicate that the proposed wide-synchronization control leads to a considerable improvement of the dynamic characteristics of the system. The aspects related to latencies and energetic requirements are also investigated. A roadmap for further developments of the concept is finally discussed.**

***Index Terms*—damping, frequency control, grid-forming, inter-area oscillations, wide-area control.**

I. Introduction

WIDE-area control schemes are complex yet powerful tools for the enhancement of stability and robustness of large interconnected power systems. The main actuators of conventional wide-area control schemes are typically the power system stabilizers (PSS) of synchronous machines. These controllers realize a supplementary exciting control action on the synchronous machines of power plants, and they have been extensively used for the damping of inter-area oscillations. With the development of power electronics technology, also high voltage direct current (HVDC) stations and flexible AC transmission system (FACTS) devices have been included as actuators within wide-area control systems [1]–[6]. Recently, also renewable power plants and storage systems started to be considered as possible actuators for the wide-area control [7]–[9]. In this context, the grid-forming technology for the control of power converters can represent the key-enabler for the definition and the implementation of more advanced wide-area control schemes. In fact, the principle behind the PSSs of synchronous machines is inherently characterized by an indirect action upon the machine, realized through the excitation system. The concept of grid-forming, instead, introduces a significant flexibility in the formulation of the power-angle control for converter synchronization. The control law must be defined according to specific requirements, but it can also be designed to implement extended features and advanced control actions, including additional controls based on local as well as remote signals. With this possibility of directly acting upon the power-angle relationship, the grid-forming technology represents therefore the opportunity for the realization of innovative and enhanced wide-area control architectures. The grid-forming control is a promising technology for the control of power converters, which is currently the focus of research, pilot projects and experimentation [10]–[14]. Two common grid-forming schemes are the droop control and the virtual synchronous machine [15]–[19]. The droop-based control provides grid-forming functionalities through droop controls on active and reactive power, whereas the virtual synchronous machine is generally based on the emulation of the dynamics of the synchronous machines. The damping characteristics of power systems with high shares of grid-forming converters have been studied in different works [20]–[22]. However, the participation of grid-forming converters in the wide-area control of interconnected power systems has not been either proposed nor investigated yet.

The contribution of the work is the presentation of a novel wide-area control for power systems with grid-forming converters. The concept, designated as wide-synchronization control (WSC), relies on an extended power-angle control for grid-forming converters. The synchronization unit of the converter includes an additional integral action and a remote reference signal, which is provided by a central unit for wide-synchronization. The proposed WSC is a response-based control scheme, which can be regarded as an enhancement of the synchronizing mechanism between sources, typically realized by the physical exchanges in the power system itself. The paper is then organized as follows. In Section II, the concept of the wide-synchronization control is first introduced, presenting a theoretical proof of the principle and deriving an effective tuning methodology. In Section III, the wide-synchronization control is applied to the large-scale dynamic model of the biggest interconnected power system in the world, providing also a critical investigation of time delays and energetic feasibility of the control. In Section IV, challenges and perspectives for further developments of the proposed wide-synchronization control are finally discussed.

II. Wide-Synchronization Control

A. Concept

The participation of grid-forming converters in the wide-area control of the system can be realized through the concept of wide-synchronization. The architecture is shown

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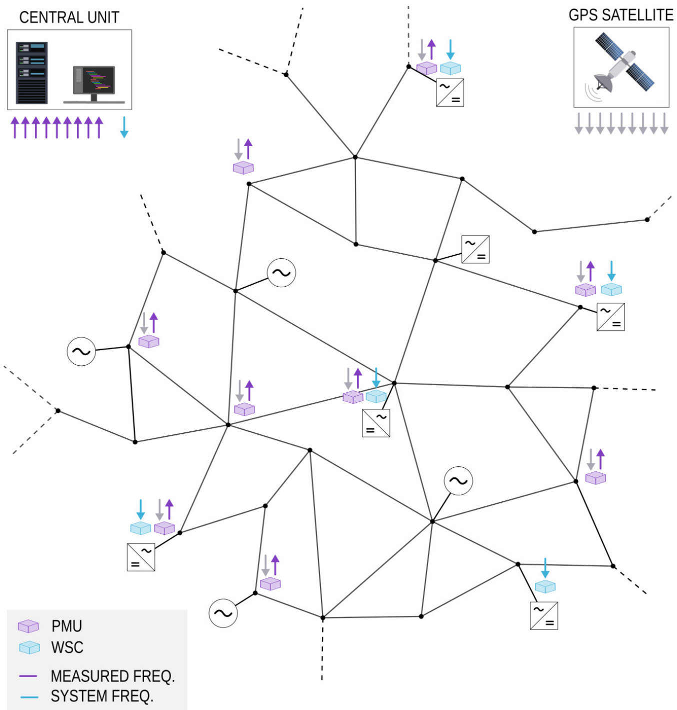

Fig. 1. Conceptual architecture of the wide-synchronization control.

in Figure 1. A central computation unit receives a set of frequency measurements from the phasor measurement units (PMU) distributed in the system, including those installed at synchronous machines and grid-forming converters locations. The central unit processes the received signals and computes the average value, which represents an estimation of the average frequency of the system ω_{sys}. This signal is then sent to the actuators of the scheme, which are the grid-forming converters participating in the wide-synchronization control. In Figure 1, the blue arrow corresponds to the frequency of the system ω_{sys} elaborated by the central unit, while the purple arrows correspond to the frequencies measured by the PMUs and sent to the central unit. The signals can be exchanged in both directions through a high-speed fiber-optic communication network. The grid-forming converters participating in the control implement an extension of the power-angle control loop, using the remote signal provided by the central unit. The wide-synchronization control is illustrated in Figure 2.

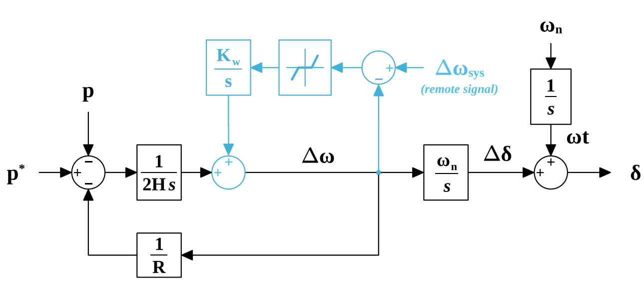

Fig. 2. Grid-forming synchronization loop for wide-synchronization.

The block diagram shows in black a fundamental swing-based grid-forming control, where the power-angle control loop responsible for synchronization emulates the typical swing dynamics of synchronous machines. This basic control is extended for wide-synchronization control with an additional control action, directly included within the power-angle loop. The additional control is basically an integrator with a given gain, which processes the difference between the average frequency of the system, sent remotely by the central unit, and the internal frequency of the grid-forming converter. The integrator will operate as long as the input is different from zero, and thus it will act to cancel the deviation between the internal frequency of the grid-forming converter and the average frequency of the system. Since the internal frequency of the converter and the frequency of the system will eventually reach the same value, the proposed control will not affect the steady-state response of the grid-forming converter. The output of the integrator is added to the first integrator of the synchronization loop, which would represent the internal frequency of the grid-forming converter without the wide-synchronization control. The proposed extension is indicated in blue in the diagram of Figure 2. For sake of simplicity in the modelling, the remote signal provided by the central unit is assumed to be the deviation from the rated frequency of the system $\Delta\omega_{sys}$, instead of the system frequency ω_{sys} itself. The additional control also includes a dead-band, to perform the control actions only when outside a determined range of ordinary operation.

According to the illustrated concept, the grid-forming converters involved in the control will be guided to be as much as possible coherent with the average transient behaviour of the system. It is then expected that the oscillatory characteristics of the entire system will be reasonably improved, with enhanced synchronizing transients between the sources and increased damping levels in the system.

B. Proof

As proof of concept, it is possible to consider a generic couple of grid-forming converters i and j connected to the system, both participating in the wide-synchronization control as described before. According to the diagram of Figure 2, it is possible to express the time derivative of the internal frequency of the grid-forming converter as:

$$\Delta\dot{\omega} = \frac{1}{2H}\left(p^* - p - \frac{\Delta\omega}{R}\right) + K_w\left(\Delta\omega_{sys} - \Delta\omega\right) \quad (1)$$

where the discontinuous effects of the dead-band have been neglected. The average frequency of the system $\Delta\omega_{sys}$ computed by the central unit is given by:

$$\Delta\omega_{sys} = \frac{1}{N}\sum_{k=1}^{N}\Delta\omega_k \quad (2)$$

where N is the number of the observed frequencies provided by the PMUs in the system. Substituting (2) in (1), and applying it for the two grid-forming converters i and j:

$$\Delta\dot{\omega}_i = \frac{1}{2H_i}\left(p_i^* - p_i - \frac{\Delta\omega_i}{R_i}\right) + \underbrace{K_w\left(\frac{1}{N}\sum_{k=1}^{N}\Delta\omega_k - \Delta\omega_i\right)}_{\text{proposed control}} \tag{3}$$

$$\Delta\dot{\omega}_j = \frac{1}{2H_j}\left(p_j^* - p_j - \frac{\Delta\omega_j}{R_j}\right) + \underbrace{K_w\left(\frac{1}{N}\sum_{k=1}^{N}\Delta\omega_k - \Delta\omega_j\right)}_{\text{proposed control}} \tag{4}$$

For sake of demonstration, the gain K_w is assumed equal for both converters. Focusing only on the contribution of the proposed additional control, the mutual relationship between the two grid-forming converters can be obtained as difference of (3) and (4), resulting in:

$$\Delta\dot{\omega}_i - \Delta\dot{\omega}_j = K_w\Bigg[\cancel{\frac{1}{N}\sum_{k=1}^{N}\Delta\omega_k} - \cancel{\frac{1}{N}\sum_{k=1}^{N}\Delta\omega_k} + \Delta\omega_j - \Delta\omega_i\Bigg] = -K_w\left(\Delta\omega_i - \Delta\omega_j\right) \tag{5}$$

The minus sign in (5) indicates that the wide-synchronization control is opposite to the existing frequency difference between the sources. The proposed control will then act to contrast the differences between the frequencies of the grid-forming converters involved in the wide-area control, driving them to be coherent with each other and thus improving the dynamic characteristics of the system.

C. Tuning

The gain K_w for wide-synchronization control of a grid-forming converter can be tuned according to some basic considerations. The methodology can be derived referring to the case of a single source connected to a bulk system. This approach is known as infinite bus modelling, and it implies that angle and frequency variations are locked ($\Delta\delta_{ib} = 0$ and $\Delta\omega_{ib} = 0$). This can be considered equivalent to neglecting the dynamics of the bulk system. According to Figure 2, the power-angle control of a WSC converter is defined by (1) and by:

$$\Delta\dot{\delta} = \omega_n\Delta\omega \tag{6}$$

where ω_n is the nominal angular frequency of the system. It is worth observing that all equations are expressed in per unit, so the angular frequency corresponds numerically to the frequency. Considering the prevalence of the bulk system over the small contribution of the grid-forming converter, under the assumptions related to the infinite bus approach, the average value of the frequency variation can be approximated as $\Delta\omega_{sys} \simeq \Delta\omega_{ib} = 0$, and then (1) simplifies in:

$$\Delta\dot{\omega} = \frac{p^* - p}{2H} - \left(\frac{1}{2HR} + K_w\right)\Delta\omega \tag{7}$$

Differentiating (6), substituting (7) for $\Delta\dot{\omega}$ and rearranging, it results:

$$\Delta\ddot{\delta} + \left(\frac{1}{2HR} + K_w\right)\Delta\dot{\delta} + \frac{\omega_n}{2H}p = \frac{\omega_n}{2H}p^* \tag{8}$$

For the assumptions related to the infinite bus approach, the active power p transmitted by the source to the system can be expresses for small variations as $p = K_s\Delta\delta$, where K_s is known as synchronizing coefficient [23]. Inserting in (8), it results:

$$\Delta\ddot{\delta} + \left(\frac{1}{2HR} + K_w\right)\Delta\dot{\delta} + \left(\frac{\omega_n K_s}{2H}\right)\Delta\delta = \frac{\omega_n}{2H}p^* \tag{9}$$

which corresponds to the characteristic equation of a second order dynamic system:

$$\ddot{x} + 2\zeta\omega_f\dot{x} + \omega_f^2 x = F \tag{10}$$

where ζ is the damping ratio and ω_f is the undamped frequency of oscillation. Comparing (9) and (10), it is easily derived:

$$\zeta = \frac{1}{2\omega_f}\left(\frac{1}{2HR} + K_w\right) \tag{11}$$

$$\omega_f = \sqrt{\frac{\omega_n K_s}{2H}} \tag{12}$$

It can be noted that the gain K_w modifies the damping ζ of the system, but not the natural frequency of oscillation ω_f. Equation (11) can be solved for K_w, leading to:

$$K_w = 2\omega_f\zeta - \frac{1}{2HR} \tag{13}$$

Considering that the damping ratio of the system without the additional control (i.e. for $K_w = 0$) is given by:

$$\zeta_s = \frac{1}{2\omega_f}\frac{1}{2HR} \tag{14}$$

equation (13) can be rewritten as:

$$K_w = 2\omega_f\left(\zeta^* - \zeta_s\right) \tag{15}$$

where ζ^* is a target damping ratio, which can be conveniently used for the tuning of the control. Equation (15) can be in fact used to tune the gain K_w in two possible ways. The first possibility is to focus on the detail of the grid-forming converter, and represent the rest of the system in a simplified way and with limited information, f.i. following the infinite bus approach. The computation of ω_f and ζ_s would require in this case only the knowledge of some basic parameters of the grid-forming control and an elementary estimation of the interconnection with the grid. The second possibility is to look at the power system at large, and perform an overall modal analysis of the system in its complex for the determination of the oscillation modes. In this case, the relevant information about ω_f and ζ_s can be extracted from the results of the analysis. This approach can be appropriate for the tuning of the gain K_w in the case of actual power systems, obtaining a detailed knowledge of the oscillation modes through the modal analysis, and then applying equation (15) with the data extracted from the eigenvalues. Without a detailed knowledge of the oscillation modes of the system, a generic approach at system level could be the following. The range of interest for power-frequency oscillations in large power systems is typically 0.1 to 2.0 Hz [23], covering both local and inter-area oscillation modes. Considering this range of frequencies as ω_f, and assuming the worst-case scenario for the system with poor damping properties $\zeta_s = 0.05$, it is possible to calculate the values of the gain K_w for an ideal target damping ratio of $\zeta^* = 1$. The values of K_w calculated with (15) according to this generic methodology are reported in Table I. From the indicated values, it results a possible range of 1 to 25 pu.

TABLE I
WIDE-SYNCHRONIZATION GAIN FOR $\zeta^* = 1$ AND $\zeta_s = 0.05$

Oscillation frequency ω_f	*Gain* K_w *(pu)*
0.1 Hz (0.6 rad/s)	1.2
0.2 Hz (1.2 rad/s)	2.4
0.3 Hz (1.9 rad/s)	3.6
0.4 Hz (2.5 rad/s)	4.8
0.5 Hz (3.1 rad/s)	5.9
0.6 Hz (3.8 rad/s)	7.2
0.7 Hz (4.4 rad/s)	8.3
0.8 Hz (5.1 rad/s)	9.5
0.9 Hz (5.6 rad/s)	10.7
1.0 Hz (6.3 rad/s)	11.9
1.1 Hz (6.9 rad/s)	13.1
1.2 Hz (7.5 rad/s)	14.3
1.3 Hz (8.2 rad/s)	15.5
1.4 Hz (8.8 rad/s)	16.7
1.5 Hz (9.4 rad/s)	17.9
1.6 Hz (10.1 rad/s)	19.1
1.7 Hz (10.7 rad/s)	20.3
1.8 Hz (11.3 rad/s)	21.5
1.9 Hz (11.9 rad/s)	22.7
2.0 Hz (12.6 rad/s)	23.9

The proposed tuning methodology is approximate yet simple, requiring only the knowledge of a few parameters. The tuning can be done either system-wise or area-wise, considering the whole power system or restricting the analysis to a given part. In both cases, a proper tuning of the control is expected to determine a significant coherence of the sources, even when belonging to very different areas of the system. In Section III, it will be shown that this generic methodology can be properly applied to the actual case of large power systems, obtaining good performances of the control with a considerable improvement in the damping characteristics of the system.

D. Latency

The principle of the wide-synchronization control is introduced for the ideal case of no time delays. The qualitative assessment of the expected impact of latencies can be done focusing on the behaviour of a generic grid-forming converter implementing the wide-synchronization control. Figure 3 shows a detail of a representative under-frequency transient. Dashed lines indicate the ideal case of no latencies, solid lines denote the actual case of latencies in the system. In the ideal case of no latencies, the remote signal provided by the central unit starts to change instantly at the beginning of the transient (dashed blue line in Figure 3). In presence of time delays, the remote signal received by the control system of the grid-forming converter would refer to past values of the

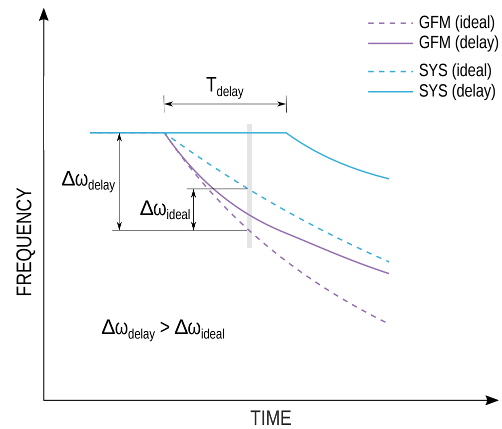

Fig. 3. Impact of latencies on wide-synchronization.

average frequency of the system. Focusing on the first time delay span right after the beginning of the transient, it can be observed that, at a given instant, the difference between the internal frequency of the grid-forming converter (dashed purple line) and the average frequency of the system in the actual case of control with time delays (solid blue line) would be larger than in the ideal case of no latencies in the system (dashed blue line). From the block diagram of Figure 2, it is easily derived that the proposed wide-synchronization control is equivalent to a transient change in the active power reference of the grid-forming converter. Consequently, if the difference between the internal frequency of the converter and the average frequency of the system is larger, the transient amount of injected power will also be larger. This increase in the power delivered during the transient ultimately corresponds to an increase of the inertial effect in the system, according to the physical principle of inertia provision. By effect of the wide-synchronization control, the dynamic behaviour of the grid-forming converter will be then characterized by an higher inertia in presence of latencies in the system (solid purple line in Figure 3). A similar consideration can be done in the case of over-frequency transients, leading to the same conclusions.

Since the main effect of the latencies is a change of the transient active power delivered by the grid-forming converter, the wide-synchronization control is expected to have a certain robustness against the possible negative effects of time delays.

The validity of the proposed wide-synchronization control in presence of latencies can be also demonstrated with analytical considerations. Following a similar approach of Section II-A, the relationship between two generic grid-forming converters considering the time delays is given by:

$$\Delta\dot{\omega}_i(t) - \Delta\dot{\omega}_j(t) = -K_w\Big[\Delta\omega_i(t) - \Delta\omega_j(t)\Big] + \underbrace{K_w\Big[\Delta\omega_{sys}(t-T_{di}) - \Delta\omega_{sys}(t-T_{dj})\Big]}_{\text{term due to latencies}} \tag{16}$$

where the dependence on the time has been made explicit. The round-trip delays for the remote signal $\Delta\omega_{sys}$ processed by the two grid-forming converters are indicated as T_{di} and

T_{dj}, respectively. Even if the delays are generally different, in practice they could be only some milliseconds apart. The term due to the latencies in (16), therefore, can be reasonably assumed to be small, since it is proportional to the difference between two values of the same quantity $\Delta\omega_{sys}$, obtained only a few milliseconds apart. The impact of latencies on the control performances will be limited, and the wide-synchronization control will preserve the effectiveness in contrasting the frequency differences between the parts of the system.

It is worth to notice that the impact of time delays is an aspect which should be carefully taken into account, and assessed for each individual case with detailed studies.

III. Application Example

The proposed wide-area control with grid-forming converters is applied to the actual case of the European power system. The Continental Europe synchronous area is the largest interconnected system in the world, spanning from the Iberian Peninsula to Turkey direction West–East, and from Denmark to Italy direction North–South. This extent makes the European system particularly interesting for the application of wide-area measurement, protection and control schemes. To the purposes of this work, the large-scale dynamic model provided by the ENTSO-E is considered and properly adapted. Table II summarises the most relevant information about the dynamic model used to represent the European power system [24]. More details about the original model can be found in [24]–[27]. This model is further developed and modified, integrating a given amount of grid-forming generation sources, as replacement of conventional synchronous generation, and implementing the wide-synchronization control architecture. The methodology for the integration of non-synchronous generation into the dynamic model of the European power system is based on a country-wise selection of the synchronous machines to be replaced with non-synchronous generation sources. The selection is performed according to the target integration level, the average generated power and the relative contribution of the given country. More details about this methodology can be found in [28].

TABLE II
Overview of the European system dynamic model

Country	*Buses*	*Lines*	*Loads*	*Gener.*	*Contr.*
Albania AL	331	184	187	-	-
Austria AT	104	84	49	22	58
Bosnia Herzegovina BA	265	277	195	6	15
Belgium BE	140	171	49	23	60
Bulgaria BG	797	775	489	7	12
Switzerland CH	193	222	145	21	60
Czech Republic CZ	288	91	163	26	73
Germany DE	3586	3393	1446	307	874
Denmark DK	248	239	124	13	24
Spain ES	1385	1320	915	86	213
France FR	2495	2583	1680	118	315
Greece GR	1114	1126	473	22	66
Croatia HR	300	295	240	3	9
Hungary HU	120	72	45	20	24
Italy IT	1215	792	611	164	428
Luxembourg LU	38	28	20	3	1
Montenegro ME	94	65	53	-	-
North Macedonia MK	148	135	108	2	-
Netherlands NL	994	890	347	64	184
Poland PL	610	971	287	52	108
Portugal PT	409	355	238	7	15
Romania RO	1089	1178	826	13	15
Serbia RS	527	587	348	17	45
Slovenia SI	135	94	99	3	9
Slovakia SK	48	41	35	10	28
Turkey TR	4517	1943	2129	137	381
	21190	17911	11301	1146	3017

A. Dynamic Analysis

The dynamic simulations of the European power system with wide-synchronization control are performed in Neplan [29]. The software offers several built-in capabilities and models, but the general wide-area control feature and the specific grid-forming model with extended power-angle control are not available. For that, the wide-synchronization control architecture (Figure 1) is implemented with an external C# application, linked to the computational core of the software through the available APIs, and the power-angle loop of grid-forming converters for wide-synchronization control (Figure 2) is implemented with user-defined equations and applied to the corresponding grid-forming sources. The European system is then simulated for a power imbalance of 1 GW generation in the western part, corresponding to an actual incident occurred in the system and used by the ENTSO-E for the validation of the original model [25]. The sudden generation loss of 1 GW is then applied within the simulation model of the European system, causing a frequency transient and sustained oscillations between the areas. The dynamic analysis is performed for three scenarios: all synchronous generation; 70% integration of grid-forming converters; 70% grid-forming and application of the proposed wide-synchronization control. For the gain K_w of the WSC control in the grid-forming converters, the generic tuning methodology described in Section II-C is here applied. According to the given indications, it is set $K_w = 10$ pu for all the grid-forming converters participating in the wide-synchronization control. This gain is chosen as an intermediate value within the identified range of 1 to 25 pu. The dead-band limits are set to ± 0.0004 pu, corresponding to a frequency deviation of ± 20 mHz in a 50 Hz power system [30]. The parameters H and R of the grid-forming control are determined according to the characteristics of the dismissed synchronous power plants: the main characteristics of inertial response and frequency containment reserve of the system are thus preserved. The results of the simulations are shown in Figure 4 to Figure 10. The plots in Figure 4 to Figure 6 display the recorded frequencies of all grid-forming converters and synchronous machines connected to the system, and the average frequency of the system (dashed blue line). This frequency corresponds to the signal $\Delta\omega_{sys}$, computed by the central unit and sent to the grid-forming converters for wide-synchronization control. The recorded frequencies are coloured according to conventional geographical groups,

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respectively western, central and eastern areas.

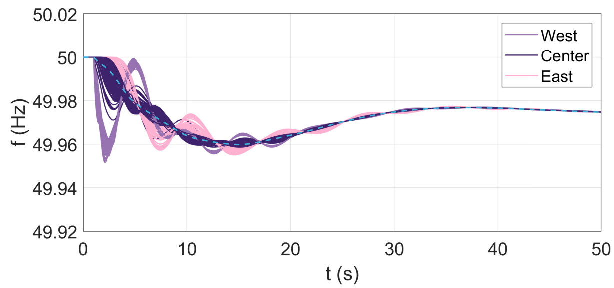

Fig. 4. Frequencies of the simulated system – all synchronous generation.

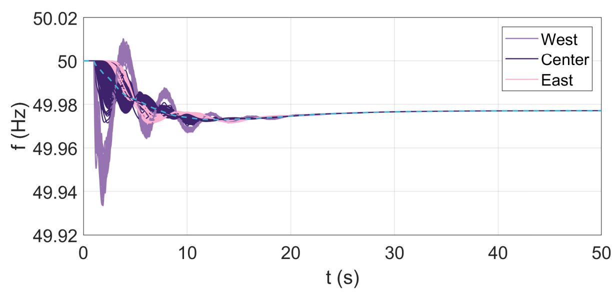

Fig. 5. Frequencies of the simulated system – grid-forming integration.

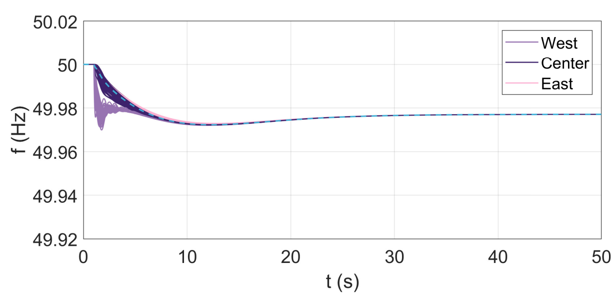

Fig. 6. Frequencies of the simulated system – wide-synchronization control.

The comparison between the basic case of all synchronous generation (Figure 4) and the case of high integration of grid-forming converters (Figure 5) indicates that the overall dynamic behaviour of the system with grid-forming sources is closer to a second-order response, exhibiting inter-area oscillations with higher frequencies and smaller decaying time. The application of the proposed wide-synchronization control (Figure 6) demonstrates a remarkable improvement of the dynamic characteristics of the system. The damping is significantly increased, the oscillations following the power imbalance are almost all eliminated, and the sources are strongly coherent with each other, even when located in very far positions across the system. The frequencies of central and eastern Europe groups are all around the average frequency of the system. The frequencies of the western Europe group exhibit instead a transient deviation from the reference frequency provided by the wide-synchronization control. However, the initial deviations are effectively contained, and quickly cleared by effect of the additional integral actions included into the grid-forming converters for wide-synchronization. After that,

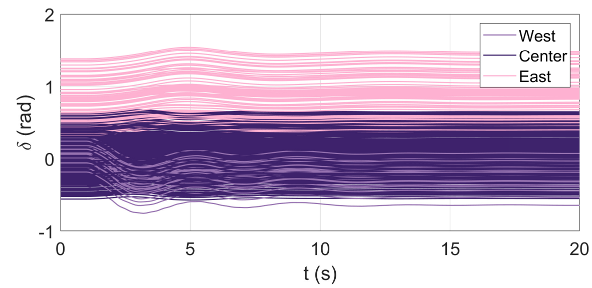

Fig. 7. Relative phase angles – grid-forming integration.

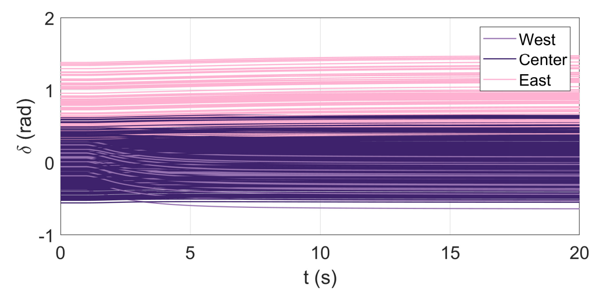

Fig. 8. Relative phase angles – wide-synchronization control.

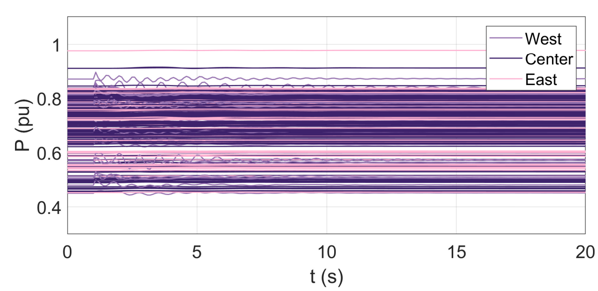

Fig. 9. Active powers – grid-forming integration.

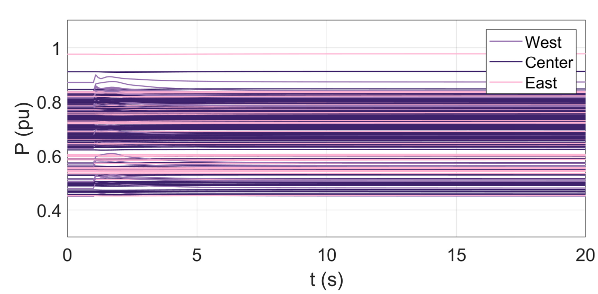

Fig. 10. Active powers – wide-synchronization control.

the frequencies of the western Europe group are aligned with the average frequency of the system. The localized frequency transient suggests the opportunity of adaptive control schemes for provision of local inertial response, but this is out of the scope of this work. It can be finally noted that the application of the proposed wide-synchronization control determines also a relevant improvement in the values of the instantaneous frequency deviations (frequency nadir). Even if the considered contingency is not critical for the system, the effect of the wide-synchronization control is expected to contribute positively to the stability of the system, contrasting the oscillations and reducing the instantaneous frequency deviations.

For a more comprehensive overview of the dynamic performances of the grid-forming converters involved in the wide-synchronization control, the phase angle and the active power output of the grid-forming sources are also reported in Figure 7 to Figure 10, respectively. The phase angles are computed as relative displacements with respect to a selected common reference. The active powers are normalised to the per unit of the rated power of the corresponding grid-forming converter. The simulation results show that the application of the wide-synchronization control determines a containment of the angle differences between the grid-forming sources located in the areas of the system, especially during the first seconds of the transient (Figure 7 and Figure 8). This observation indicates the increase of the angle stability of the system as a further advantage of the wide-synchronization control. In terms of active power, it can be observed that the power output of some grid-forming converters is affected by prolonged oscillations (Figure 9). When the grid-forming converters participate in the wide-synchronization control, the oscillations in the power output are almost completely eliminated (Figure 10). Equipments and energy sources behind the grid-forming converters will therefore benefit from the more stabilised active power output, which is accomplished by the proposed wide-area control. Moreover, the simulation results show that, in this case, the application of the wide-synchronization control do not determine any critical overloading condition for the grid-forming sources involved in the control.

B. Latency Effect

Wide-area control schemes have necessarily to deal with latencies and time delays, and in general they should be based on fast devices and communication infrastructures [31]–[34]. Time delays might have in fact a negative impact on the performances of the control [35]–[39]. Possible countermeasures are lead-lag blocks and band-pass filters in the control units. The aspects related to latencies and time delays in wide-area control are here acknowledged, and addressed with a representative study on the considered application example. The delays in the proposed wide-synchronization control are basically due to the time required by the following steps: acquisition of local frequency measurements through PMUs; communication of the local frequencies to the central computation unit; elaboration of the average system frequency; communication of the reference frequency to the local grid-forming actuators; execution of the control actions. For sake of simplicity, the total time delay is approximately divided in half within the whole cycle, as shown in Figure 11.

An estimation of the total delay can be based on the following considerations. The reporting latency of PMUs depends on the accuracy, and it can be expected in the range of 100-200 ms. Time delay for fiber-optic communication cables is around 5 μs per kilometer. The CPU elapsing time for data processing in the central unit can be estimated around 10-20 ms, since it is just needed a simple computation of the average

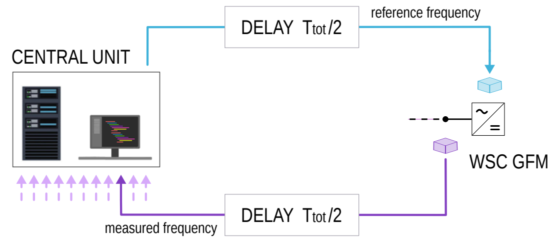

Fig. 11. Representation of delays in the wide-synchronization control.

value of the received frequencies. The time required to execute the commands in the local control system is approximately in the range 10-50 ms. Considering these typical ranges and the geographical extent of the European power system, a total time delay can be roughly estimated as 180 ms. This value is determined considering the possible longest distance to the central computation unit, and it is conservatively applied to all the sources of the systems. The estimated delay of 180 ms is also compatible with the delays of actual wide-area control implementations [4] [5], which are found in the order of 100 ms. The assessment of the total delay is based on a deterministic approach, and it refers to a constant average value. In reality, time delays are subject to uncertainties, and they can also differ from area to area in case of large power systems. For that, two different conditions are assumed for investigation: a fixed delay of 180 ms for all the involved sources of the system, and a random set of delays generated in the range 300 ms to 1 s. The purpose of the second condition is twofold: checking the robustness of the proposed control against high delays, and examining the possible effect of delay uncertainties with random distributions.

Time delays can be included in the mathematical model of the system in different ways: the Padé approximation is an approach which has been commonly used, and has proved good phase accuracy [40] [41]. Approximations with same degree at numerator and denominator exhibit a jump at initial conditions, therefore it is preferable a strictly second order approximation:

$$G_{delay}(s) = \frac{6 - 2T_d s}{6 + 4T_d s + T_d^2 s^2} \tag{17}$$

where T_d is the given time delay. The transfer function in (17) is used to represent the delay blocks in Figure 11: it is formulated in the time-domain, and then inserted into the user-defined models of the sources involved in the wide-synchronization control. The results of the simulations including the latencies are shown in Figure 12 and Figure 13, respectively for fixed and random delays.

The results indicate that the global effect of the latencies in the wide-synchronization control is an increase of the inertial response in the system. The usage of a delayed reference frequency within the grid-forming control determines a clear prolongation of the transient actions, with a consequent increase of the inertial effect in the system. This holds for both fixed and random time delays, where higher values of the rate of change of frequency (RoCoF) are observed. The wide-synchronization control proves to be robust also in the

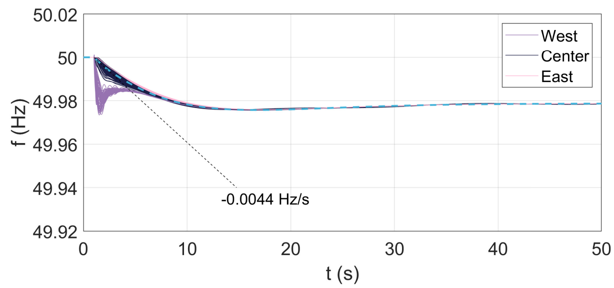

Fig. 12. Frequencies of the system – Latencies fixed to 180 ms.

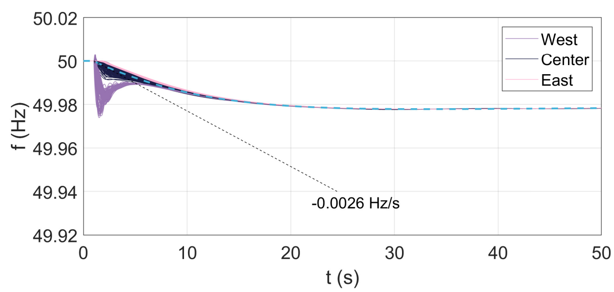

Fig. 13. Frequencies of the system – Latencies in the range 300 ms–1 s.

case of variable and very high time delays. The simulations with the latencies agree with the consideration reported in Section II-D, proving the increase of the inertial effect as side effect of the latencies in the system. Extensive simulations performed by the authors also confirm this observation, but they are not included here for brevity. The general increase of the inertial effect implies that the sources participating in the wide-synchronization control might be requested to provide an higher amount of energy, depending on the entity of the delays. This poses the attention on the effort in terms of energy required to the physical sources behind the grid-forming converters. The aspects related to the energetic feasibility of the proposed wide-synchronization control are discussed in Section III-C.

C. Energetic Feasibility

The proposed wide-synchronization control will generally require a transient modification of the power output of the grid-forming converters participating in the control scheme. According to the illustrated concept, sources with a frequency smaller than the reference frequency of the system will be demanded to deliver more transient power, while sources with a frequency greater than the reference frequency will be demanded to deliver less transient power. The physical generation source behind the grid-forming converter should be then capable of providing a specific amount of power and energy, when required. The aspects related to the energetic feasibility of the proposed wide-synchronization control are here acknowledged, and addressed with a representative study for the considered application example. For each grid-forming converter participating in the wide-synchronization control, the output active power is recorded and post-processed with integration over time, determining the total energy delivered by the physical source. For the generic grid-forming converter i, the cumulative energy E_i is computed approximating the integral of the power via the trapezoidal method:

$$E_i = \frac{\Delta t}{2} \sum_{k=1}^{N_S} \left(P_k + P_{k-1} \right) \tag{18}$$

where Δt and N_S are respectively fixed time step and number of steps in the numerical solution provided by the dynamic analysis. The physical sources behind the grid-forming converters are here assumed to have the basic energetic availability required, i.e. to be already designed for being grid-forming itself. Therefore, the focus of the energetic feasibility study is rather the additional amount of energy, which would be required to the physical sources when implementing the wide-synchronization control. For that, the difference between the energies required to the grid-forming sources in the two scenarios, with and without wide-synchronization control, is considered for investigation. The cumulative energies are then computed using (18) on the numerical results of these two scenarios, which have been reported graphically in Figure 5 and Figure 6, respectively. The results of the computation are summarized in Figure 14. The plots show increase or decrease of the energetic engagement for each grid-forming converter participating in the wide-synchronization control. The results are provided both in absolute and percentage values.

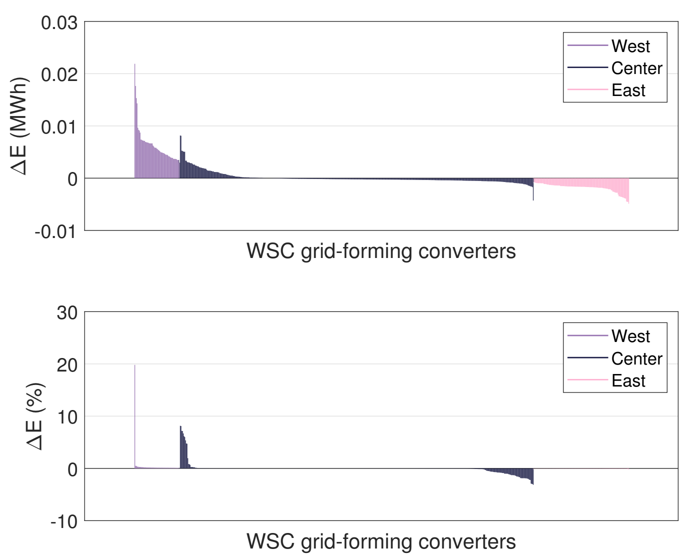

Fig. 14. Energy differences in absolute and percentage values.

In terms of absolute values (top plot in Figure 14), it can be easily visualized that the sources near the generation loss occurred in the system (western and part of central Europe) provide more energy than in the case of no wide-synchronization control. The sources far away from the generation loss (eastern and small part of central Europe) provide instead less energy. The majority of the remaining sources in the system is barely affected by the application of the control. It can be noted that the wide-synchronization control will generally require a transient modification of the active power to those grid-forming sources with a relevant frequency difference, which are typically sources located in areas very far away from each other. In terms of percentage values (bottom plot in Figure 14), it can be observed that only a few generation sources are requested to provide an amount of energy much higher than the energy they would have provided in the case of no additional wide-area control. This observation corroborates the energetic feasibility of the proposed wide-synchronization control, pointing out that the engagement of the physical sources would only have a limited difference in comparison with the energy required by the operation of the grid-forming control itself. This also suggests that the proposed wide-synchronization control can remain effective, even if a limitation of the active power will be necessarily applied to some sources for energetic reasons during the transient. It should be finally noticed that the value assigned to the gain K_w of the additional integral action can have an impact on the transient energy requested to the physical sources, indicating the need for considering also the energetic aspect when designing the control.

IV. Discussion

The basic idea behind the proposed wide-synchronization control is the participation of grid-forming converters in the wide-area control of the system. The power-angle control responsible for synchronization is extended with an additional control action, using a remote frequency signal for wide-synchronization. The grid-forming converters can be then coordinated by a centralized supervisor entity, aware of the conditions of the different parts, and capable of guiding the widespread sources for the common sake of the system. In this sense, the presented wide-synchronization control is a parallel communication channel for the propagation of the frequency information in the system [42] [43], and it can be regarded as supplement to the physical way of synchronizing and communicating of the sources, which is ultimately represented by the power system itself [44] [45].

The purpose of the article is the initial presentation of the concept: the proposed wide-synchronization control can be further developed in different ways, as there are several open points and questions to address. The possibility of alternative architectures is a first relevant aspect. In the paper, the case of a single computation unit for the entire system has been discussed. The proposed control might be also based on multiple computation units, one for each control area, possibly interacting with each other. The implications of multiple central units should be properly studied. The determination of the required measurements and actuators is another relevant point to further examine. Number and localization of the PMUs (for local frequency measurements) and of the WSC grid-forming converters (for local control actions) are aspects worth investigating. The definition of a defensive plan, making the wide-synchronization control more reliable and secure, is surely another complex aspect to take into consideration and accurately develop. This last point is related to a number of different aspects, particularly important from the point of view of practical implementation and operation: handling of data integrity, ensuring cyber security, containment of latencies and delays, robustness in case of element failures or severe contingencies like system splits. The study of the wide-synchronization control in presence of disturbances leading to the instability of the system is among the aspects which will be investigated in further developments of the work.

The development of wide-area monitoring, protection and control schemes generally involves both short-term and long-term objectives [46]. The previous points represent a roadmap for a further definition of the wide-synchronization control. The fundamental prerequisite is clearly the adoption of the grid-forming technology within the power systems: even though this technology has already proven to be mature enough and it is rapidly advancing, at the moment there are only very few grid-forming converters operating in the systems. It is foreseen, however, that in the next future the grid-forming will play an indispensable role in the operation of power systems with large shares of renewable energy sources. It is finally worth observing that the architecture of the wide-synchronization control could also be exploited for the realization of several other functionalities, in terms of control and protection of the system.

V. Conclusion

The grid-forming technology for power converters offers the possibility for the realization of effective wide-area controls in the power systems. The synchronization unit of the grid-forming converter can be extended with an additional integral action and a remote reference signal, which corresponds to the average frequency of the system. The proposed wide-synchronization control will act to contrast the transient differences between the sources participating in the control, even when they are widespread across the system. The application of the concept demonstrates the potential for a fundamental improvement of the dynamic characteristics of the system. The typical power-frequency oscillations following an incident can be practically eliminated, leading to high damping capabilities and a strong coherence between sources. The effects of time delays in the wide-synchronization control are also investigated: the results of the analysis indicate a general increase of the inertial response as consequence of the delays, proving the control to be robust also in the case of variable and very high time delays. The relevance of the aspects related to the energetic feasibility of the proposed concept is remarked: it is reasonable to expect that the wide-synchronization control will require only a limited transient effort to the energy sources, and that the control will remaining effective even in case of limited or missed contribution from some sources during the transient. The presented concept can be certainly further developed: a roadmap of the points to address is discussed, outlining both challenges and opportunities of the wide-synchronization control in power systems.

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