The Wide-Synchronization Control at Support of the Oscillatory Stability of Power Systems

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***Abstract*—The wide-synchronization control is a novel wide-area control involving inverter-based resources as actuators. The concept is based on the determination of a remote frequency signal, which can be used within the control systems of the converters participating in the control. In this paper, the concept of the wide-synchronization control is investigated as solution to effectively improve the oscillatory stability of the system. The results indicate that the proposed concept is capable to provide a decisive contribution in preserving the system stability, even under severe critical conditions.**

***Index Terms*—damping, oscillatory stability, wide-area damping control, wide-synchronization control**

I. Introduction

The rapid evolution of power systems is characterized by increasing penetration of renewable energy sources interfaced through power electronics, often complimented by heavily stressed conditions and serious vulnerability with respect to disturbances. The issues associated to the oscillatory stability are a major concern in this context, as the damping is expected to be undermined in future power systems scenarios. The study of the oscillatory phenomena in the system is then an important aspect to address [1]–[3], both for autonomous electrical networks [4]–[6] and large interconnected power systems [7]–[10]. The implementation of wide-area damping controls can represent an effective solution to improve the oscillatory characteristics of the power systems. Several different technologies have been considered for the actuation of the control actions, going from the power system stabilizers (PSS) of synchronous machines, to more recent technologies related to the control of power converters [11]–[15]. In this context, emerging technologies like the grid-forming control for the power converters offer a particular opportunity, given their flexibility in the formulation of the synchronization loop and in the provision of oscillations damping to the system [14]–[18].

The wide-synchronization control (WSC) is a novel concept of wide-area control for power systems with inverter-based resources as actuators [19]. The control is based on the determination of a reference frequency signal in a central computation unit, which will be sent to the control systems of the actuators for a transient modification of the active power reference. The aim of this paper is to investigate the concept of the WSC as solution for the improvement of the oscillatory stability of the system. The concept is applied to a benchmark system for the study of the oscillatory stability in power systems: the benchmark system is the well-known two-area four-generator system, and it is considered for particular controllers and configurations leading to a critical phenomenon of instability. The two-area system is used to assess the capability of the WSC to support the system in maintaining the stability even under critical conditions.

II. The Concept

The WSC can be illustrated with the conceptual representation of Figure 1. The WSC architecture is based on the determination of a specific frequency signal to be used as

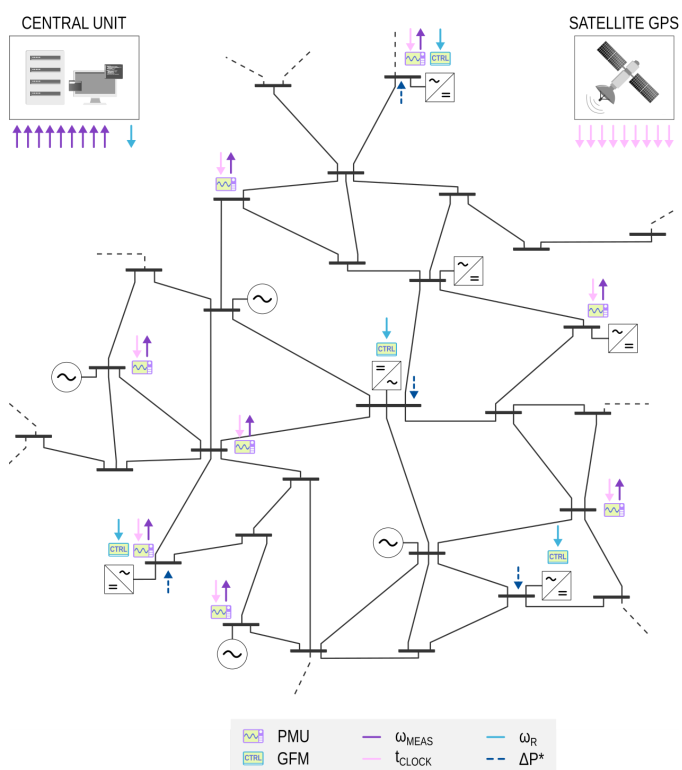

Fig. 1. Illustration of the proposed concept.

reference. This signal is elaborated by the central computation unit of the WSC, and it is the average of all the single frequencies received by the central unit from several remote measurements. Ideally, the reference signal should represent as accurately as possible the average frequency of the system. The single frequencies are provided by different phasor measurement units (PMU), which are synchronized through a GPS signal. The reference frequency ω_{r} can be expressed by:

$$\omega_{\mathrm{r}} = \frac{1}{N_m} \sum_{m=1}^{N_m} \omega_m \tag{1}$$

where N_m is the number of frequency measurements, sent from the PMUs distributed in the system to the central unit of the WSC. The reference signal ω_{r} is then sent to the inverter-based power plants which are involved in the WSC as actuators. The signal ω_{r} is compared with the local frequency at the terminal of the actuator, and the resulting difference is used to determine a change in the reference active power of the inverter-based plant. The requested change of active power Δp^* can be expressed by:

$$\Delta p^* = -K_w \left(\omega - \omega_{\mathrm{r}}\right) \tag{2}$$

where ω is the local frequency and K_w a proportional gain. At the occurrence of a frequency transient, the difference between ω and ω_{r} will be different from zero and the control will act. Eventually, this difference will return back within a normal range: the requested change in the active power will represent only a temporary adjustment of the power reference of the converter, without affecting the power sharing of the inverter-based plants participating in the WSC. Here, the grid-forming control is chosen for the assessment of the proposed wide-area damping control. Different grid-forming control schemes exist [20]–[25]. The selected scheme is a simple swing-based synchronization loop, with the replication of the typical swing dynamics of synchronous machines through the inertia constant H, and the realization of a most basic turbine/governor with the frequency droop R. The basic scheme is extended with the inclusion of an additional control action according to the principle of the WSC, accepting the remote signal ω_{r} as input. The block diagram is shown in Figure 2. In the diagram,

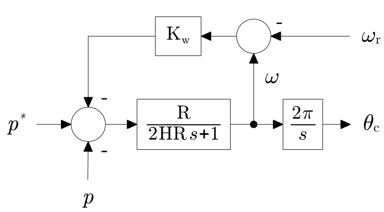

Fig. 2. Synchronization loop of a grid-forming converter for WSC.

the output variable is the command angle θ_{c} used for the synchronization of the converter. For the actuation of the WSC, the reference active power is adjusted according to (2). The implementation of the WSC will result in a transient action aimed at pushing the frequency at the terminal of the inverter-based power plant to be as much as possible close to the reference frequency provided by the central unit of the WSC. This will ultimately result in a significant coherency between the different areas of the system. It is reasonable to expect that the oscillatory characteristics of the entire system will be improved, with an increased overall damping. In the next section, the capability of the WSC in supporting the system in presence of critical conditions leading to the oscillatory instability will be assessed.

III. Benchmark System

The power system considered for the assessment of the effectiveness of the WSC under critical conditions of instability is the two-area benchmark system documented in [26] [27], where all electrical parameters and necessary data are reported. The two-area four-generator system is a well-known benchmark system, which has been widely used to investigate the phenomena related to the oscillatory stability and to demonstrate novel control strategies and concepts. The original system is modified for the purposes of the study as shown in Figure 3. Two inverter-based power plants are added in both

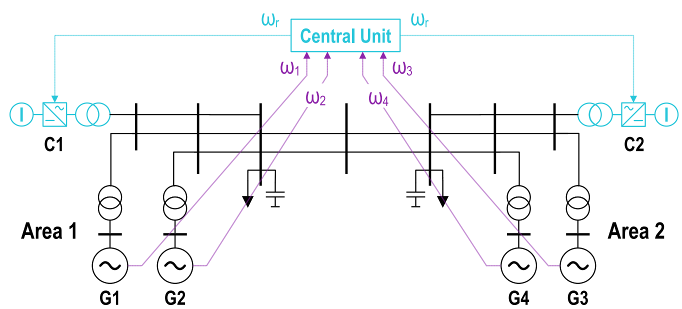

Fig. 3. Two-area four-generator benchmark system.

areas, and the architecture of the WSC is also implemented in the model. The additional plants are assumed to provide zero active and reactive power, thus preserving the symmetry and the initial steady-state conditions of the unmodified two-area system. The converters of the additional power plants are controlled with the grid-forming scheme discussed before, including the proper extension for participation in the WSC. The modified benchmark system is modelled for simulation in the phasor RMS domain. This approach has been proved to give suitable results when studying transient phenomena with slow dynamics in power systems with grid-forming converters [28]–[30], as it is the case of this paper. The power converters of the inverter-based power plants are represented as controlled complex voltage sources. The central unit is simulated with a simple model for the computation of the reference frequency as average of all the received frequency measurements. The communication system with latencies is implemented in the model according to the approach described in [19]. The model is developed within Neplan, a commercial software for power systems analysis. The main data for the simulation of the modified benchmark system can be found in

Table I. These parameters are generally selected according to the corresponding typical ranges. The gain K_w of the WSC is determined according to the simple tuning methodology described in [19]. The time delays are selected within the typical range of latencies in wide-area applications [31] [32], which is found in the range of few hundreds milliseconds. The range of 200-900 ms is therefore assumed to be representative of typical latency values. The parameters expressed in per unit values are referred to the rated power S_r of the converter.

TABLE I
SIMULATION PARAMETERS

Name	*Value*
Converter rated power S_r	100 MVA
Synchronization loop - Inertia constant H	3 s
Synchronization loop - Frequency droop R	0.05 pu
Voltage control - Proportional gain K_{pU}	1 pu
Voltage control - Integral gain K_{iU}	100 pu
Converter time constant T_c	10 ms
WSC - Proportional gain K_w	100 pu
WSC - Round-trip delay T_d	200 ms

According to [26], the two-area system can be prone to instability under specific conditions. For the purposes of the study, the following conditions are then considered: the excitation systems of the generating units implement the ST1A model, including the transient gain reduction, and no additional signals coming from the PSSs are considered. Without the regulating action of the PSSs, the system is subjected to a phenomenon of oscillatory instability. For the time-domain simulations, the disturbance is a simultaneous change of the voltage references for all the four synchronous machines of the system. This perturbation is particularly relevant for the study, because it triggers the oscillatory instability phenomenon, involving both the inter-area and the local modes of the system.

IV. Results and Discussion

The results of the time-domain simulations are shown in Figure 4 and Figure 5. As indicator of the oscillatory stability of the system, the voltage of the bus at the exact middle between the two areas is monitored and displayed. The results of the base case show the expected instability of the system (gray line). Under the considered configuration, the system is affected by a progressive amplification of the oscillations, leading to the collapse. The results of Figure 4 clearly show that the application of the WSC can effectively represent a decisive solution for preserving the stability of the system (yellow line). The oscillations occurring in the system after the disturbance are contained by effect of the transient control action requested by the WSC, and thus the proposed wide-area control can secure the stable operation of the system. When a large time delay is considered ($T_d = 900$ ms), it can be noticed that the voltage is affected by sustained oscillations after the disturbance (orange line). This result confirms the expected negative impact of latencies on wide-area damping controls, and at the same time it suggests that the proposed WSC has a certain robustness against the time delays. Even

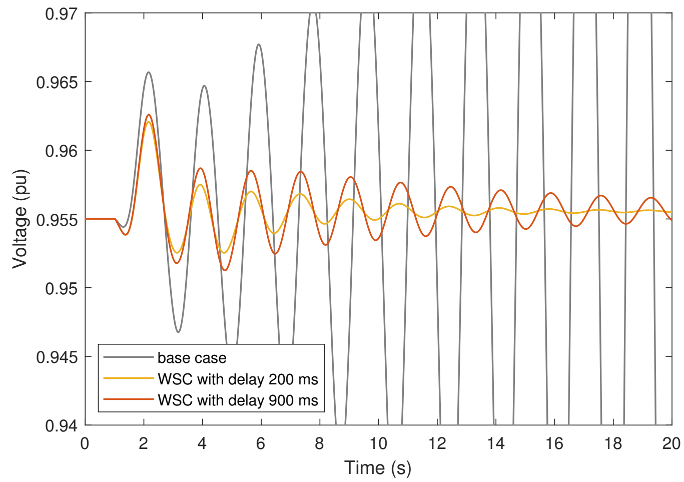

Fig. 4. Voltage at the intermediate bus – WSC one area with different time delays.

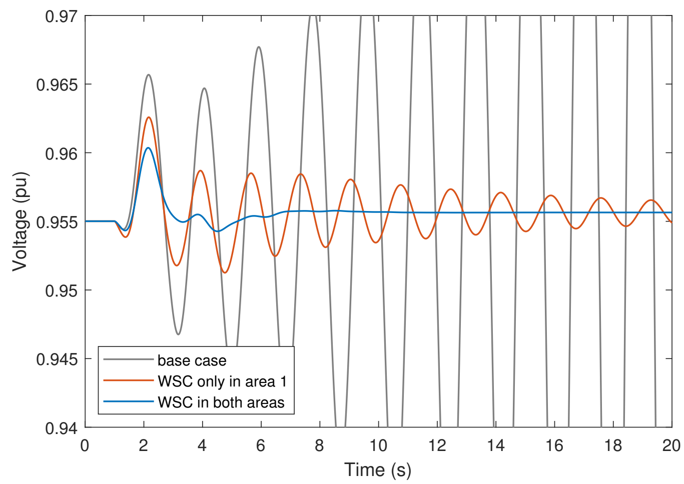

Fig. 5. Voltage at the intermediate bus – WSC in both areas with large time delay.

if the oscillations are sustained for some tens of seconds, the system has in fact still a stable response, and eventually it is able to reach again a steady-state operating point. The results of Figure 5 show that the application of the WSC in both areas can lead to a further, significant improvement of the oscillatory stability of the system. The system is no longer affected by sustained oscillations, showing a very well damped and stable transient response, even in presence of large time delays in the communication system of the investigated control. The modal analysis is also performed to complement the time-domain simulations, with the computation of the eigenvalues of the modified two-area benchmark system for the different cases considered in the study. The results shown in Figure 6 confirm the observations made with the time-domain analysis, indicating the fundamental contribution of the WSC in resolving the instability of the system.

The results of the analysis performed on the modified two-area benchmark system demonstrate the capability of the WSC

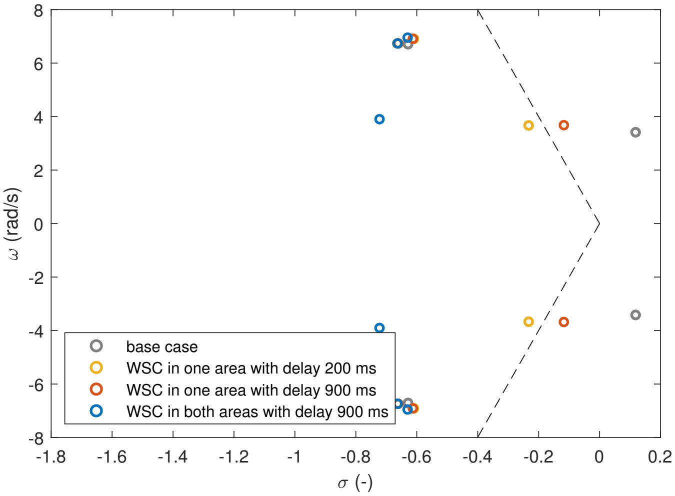

Fig. 6. Oscillation modes of the system for the different cases.

of providing a decisive contribution to the oscillatory stability of the system, even when operating under critical configurations. The participation of inverter-based power plants in the WSC results in a fundamental transient support, significantly enhancing the dynamic characteristics of the power system.

V. Conclusion

The paper investigates the application of the WSC as fundamental solution to improve the oscillatory stability of power systems. The concept of the WSC is based on the determination of a reference frequency signal, which is sent to the control systems of the actuators for a transient modification of the active power reference. For the actuation of the WSC, the grid-forming technology for the converters of inverter-based power plants has been considered. The synchronization loop of the grid-forming scheme is properly modified, realizing the transient modification of the active power requested by the WSC. The capabilities of the WSC of stabilizing the system under critical unstable conditions are assessed referring to the two-area power system, a standard benchmark system well known for the study of the oscillatory stability in power systems. The results of the time-domain analysis demonstrate that the application of the WSC can provide a decisive contribution to the oscillatory stability, securing a stable operation of the system even under critical conditions, which would otherwise lead to the collapse of the system. The results also show that the proposed WSC has a certain robustness against the negative effect of the latencies, and that the application of the WSC to multiple areas determine a significant improvement of the overall dynamic characteristics of the system.

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