Wide Area Control of Distributed Resources through 5G Communication to Provide Frequency Support

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***Abstract*—Towards the green transition of modern power systems, a massive deployment of distributed energy resources (DERs) based on renewable sources is required. These DERs are grid integrated through power electronics converters which reduce the commitment of synchronous generators and as a result, the overall inertia of the system. Maintaining the frequency stability in such low-inertia power systems is a crucial aspect for the system operators; therefore, local control schemes are integrated with conventional generators and DERs to ensure fast reaction in case of frequency disturbances so as to preserve system stability. Existing practices for maintaining the frequency stability rely on the response of a local governor controller integrated with the synchronous generators. Some new approaches introduce frequency support services by DERs, by considering the droop control and virtual inertia concept within the inverter local controller. In another approach, wide area control schemes can also be utilized to further enhance the system stability. Such a wide area control scheme is introduced in this work to coordinate the operation of DERs through 5G communication for enabling fast frequency support services. Due to the fast dynamics of a power system, a reliable and high-speed communication is particularly important for the deployment of the proposed method. Therefore, an experimental hardware in the loop setup has been developed to investigate how the communication performance can affect the stability of the power system. Moreover, a benchmarking is implemented to evaluate the frequency stability when local controllers are providing support and when the proposed wide area controller is applied under a different communication infrastructure. Experimental results demonstrate that when a reliable 5G network is used, then a significant stability improvement can be achieved by the proposed wide area controller.**

Keywords—5G communication, droop control, frequency stability, frequency support, virtual inertia, wide area control.

I. INTRODUCTION

Decarbonization of the energy system is a key priority to tackle the critical environmental threats. In this direction and towards a climate neutral economy, ambitious targets have been set for the green transition of the energy infrastructure [1] and therefore, the penetration of Renewable Energy Sources (RESs) is expected to further increase in the upcoming years. Such Distributed Energy Resources (DERs) based on renewable energy are integrated into the power system through power electronics converters [2] and cannot provide rotational inertia to the system. Furthermore, conventional synchronous generators with large rotational mass are replaced by inverter-based DERs, resulting in a significant reduction of the overall system inertia. This is a crucial aspect for power system operation, since inertia is a dominant factor that resists frequency deviation. Therefore, in modern power systems with low-inertia due to the increased RES penetration, the frequency stability is actually threatened [3], [4] and as a result, new controllers are required to enhance stability and ensure the proper operation of the system.

Conventional practices for maintaining the system frequency stability rely on the fast reaction of the local controllers of the synchronous generators. In this case, a primary level control, named governor controller [5], [6] is used to regulate the mechanical torque provided to the generator by the turbine, according to the deviation of the rotational speed of the generator. In case of a severe frequency event, the governor will regulate the response of the generator for the first few seconds after the event to stabilize the system in a new frequency. However, if the frequency does not return to its nominal value after an event or a power disturbance, then a secondary level control scheme is needed to restore the system operation. An Automatic Generator Controller (AGC) [5], [7] is usually used as a secondary control scheme that will act in a slower manner (few seconds until few minutes after the event) to restore the system frequency.

The massive deployment of RESs over the recent years, has resulted in the reduction of the system inertia and the replacement of the conventional generation units which provide frequency support with inverter-based DERs, that usually operate in a grid-following approach (synchronized with the grid voltage) [8] without being capable of supporting the frequency. The frequency support capability is limited in the case of RESs, since they usually operate at their maximum power point without any upward flexibility (i.e., capability to increase their power when there is a frequency sag event). However, in case of a DER based on an energy storage system (ESS), upward flexibility is available, and therefore, the inverter controller can be modified to provide frequency support services. This can be achieved either by adding external support functions, such as droop control and virtual inertial, to the control loop of grid-following inverters [9], [10], or by revising the inverter controller towards the grid-forming [11] or virtual synchronous generator [12] approach. In all these cases, the inverter mimics the behavior of a synchronous generator and tries to naturally respond to frequency deviations according to a droop control loop and to react against Rate of Change of Frequency (RoCoF) by incorporating the swing equation of conventional generators in the outer loop of the controller. All aforementioned approaches are based on local control schemes and can significantly improve the system frequency stability of modern power systems [3], [4].

In addition to the local controllers, recent developments considering the deployment of an advanced measuring infrastructure in modern power systems based on synchrophasor technology enable the development of Wide Area Control (WAC) approaches to improve the system operation under severe disturbances. In such WAC schemes, synchronized measurements from Phasor Measurement Units (PMUs) installed at several locations of the power system are

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received in a central controller to coordinate the operation of large-scale generators [13] and DERs [14] for damping inter-area and local voltage and frequency oscillations. In addition, a WAC scheme is developed to coordinate the provisioning of fast frequency response by generator and large DERs [15]. As a result, the aforementioned WAC approaches can further enhance system stability and are particularly important in case of low-inertia systems. In these WAC schemes, a fast and robust communication is required to take wide area actions in a time-frame of milliseconds, and thus, a wire-based (e.g., fiber-optic) communication infrastructure is usually assumed between the power substations (where the PMUs are installed) and the operator control center (where central control is executed), and between the control center and the generators and large-scale DERs. In practice, such WAC schemes are only restricted to large-scale generation plants and DERs that are connected through wire-based communication, and as a result, small- and medium-scale DERs are usually excluded due to the absence of fast and reliable communication. Even though the impact of delays due to wire-based communication has been investigated in [13], [15], where predictors have been proposed to compensate for the communication delay impact, the WAC schemes integration over wireless communication technology (e.g., 5G), to facilitate the participation of small and medium size DERs in WAC, has not been investigated in the literature.

In this work, the advanced features of 5G communication technology are incorporated, aiming to enhance the operational performance of energy systems. The contribution of this paper relies on the proposition of a WAC-based scheme able to coordinate DERs over the 5G communication. The proposed scheme receives wide area measurements from PMUs and processes them to identify power imbalances that can cause frequency disturbances. The identified power imbalance is used to calculate compensation signals for coordinating the operation of flexible DERs to prevent frequency disturbances. An important novelty of this WAC-based scheme is that the data exchange (e.g., measurements, set points) is enabled through wireless communication, thus enabling flexibility, scalability and wide deployment of such solutions considering any size of DERs. Another contribution is the development of an advanced experimental setup, where a power system digital twin is integrated with a network emulator and a digital controller in a Hardware In the Loop (HIL) configuration. In this setup, the power system digital twin is running in a real-time simulator, while the impact of the communication performance is examined by utilizing a network emulator integrated in the loop. In addition, the WAC scheme is implemented within a hardware controller to meet the strict time requirements of such applications. This HIL setup is used to evaluate the impact of different wireless communication infrastructures (e.g., 5G, 4G, etc.) on the operation of the power system when the new WAC scheme is applied. Furthermore, the power system stability is evaluated when (a) local control schemes are applied for enabling frequency support services by DERs (no communication needed) and (b) the proposed WAC scheme is integrated through wireless communication. Experimental results show that the features of 5G communication (e.g., ultra-low latency, high reliability of guaranteed quality of service) can significantly enhance power system stability, as compared to local control approaches. It is to be noted that the previous generation wireless communication technologies (e.g., 3G, 4G) are inadequate for such demanding energy applications.

The rest of the paper is structured as follows. Section II presents the local controllers for providing frequency support by generators and DERs, while the new WAC scheme for frequency support is presented in Section III. The experimental setup for cross-domain (power-communication) investigations is presented in Section IV, which is used to perform a frequency stability benchmark according to different controllers and different capabilities of the communication system. The paper concludes in Section V.

II. Local Frequency Support Schemes

Frequency stability is a crucial aspect for the operation of a power system. The frequency response of a power system is mainly determined by the response of the conventional synchronous generators connected to the system. The frequency response (f) of each generator is defined by its rotational speed ω ($\omega=2\pi f$), which is determined according to the swing equation of electrical machines [5], as given in (1),

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = P_m - P_e \quad (1)$$

where H is the normalized inertia constant of the generator (in s), ω_s is the synchronous speed of the system (in rad/s), P_m is the mechanical power provided by the turbine (in pu), and P_e corresponds to the electrical load demand served by the generator (in pu).

A frequency event (under- or over-frequency) can occur when an intense power imbalance appears. Such phenomena are observed when there is a loss of a generator or a large load (due to a fault in an equipment or in a region) and should be compensated as fast as possible in order to maintain system stability and thus prevent possible blackouts. In the initial stage of such events (e.g., first 200 ms), rotational inertia is a dominant factor that resists against such frequency deviations when a power imbalance occurs. The initial RoCoF, which is an important indicator for the frequency stability, is higher in the case of a disturbance occurring in a low-inertia system and is significantly lower in the case of a robust and high-inertia system.

After the initial stage of a disturbance, which mainly depends on the system inertia, the local primary level controllers of synchronous generators and DERs are responsible to act in order to stabilize the system frequency.

A. Frequency support by conventional generators

In traditional power systems, stability is ensured by the local controllers of the synchronous generators. A conventional synchronous generator is equipped with an exciter and a governor local controller to maintain voltage and frequency stability, respectively, as shown in Fig. 1. The exciter controller regulates the excitation current to control the reactive power injection and the voltage at the terminal of the generator. On the other hand, and to maintain frequency, the

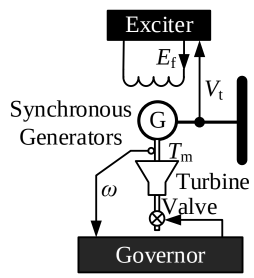

Fig. 1. Conventional synchronous generator with its local controllers.

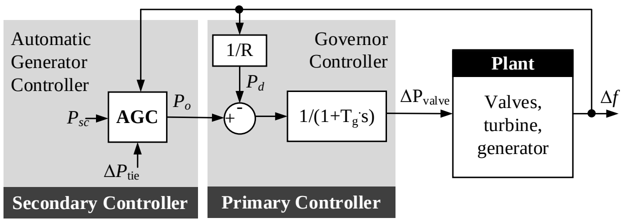

Fig. 2. Diagram of the local governor controller of synchronous generators.

governor controller regulates the mechanical power (or torque) provided by the turbine to stabilize the system.

When the power balance is maintained (P_m=P_e) at each generator, a stable frequency operation is achieved for the system according to (1), since $d\omega/dt = 0$. However, when there is a deviation of the mechanical or electrical power, a power imbalance will deviate the frequency of the system, since $d\omega/dt \neq 0$. In case of an under-frequency operation ($\Delta f < 0$), where Δf is defined as the difference between the actual frequency (f) and the nominal frequency (f_n), the governor controller should regulate the valves of the turbine to increase the mechanical power (P_m) provided to the generator. Then, according to (1), a positive power imbalance ($P_m > P_e$) will be introduced in the swing equation, accelerating the generator in order to return back to the nominal frequency. On the contrary, in the case of an over-frequency operation ($\Delta f > 0$), then the governor controller should decrease the provision of mechanical power to create a negative power imbalance ($P_m < P_e$) and decelerate the generator back to the reference value.

In case of an intense frequency disturbance, the first frequency regulation is performed by the governor controller, considering a primary level control loop based on a droop approach [5], [6], as shown in Fig. 2. The governor controller senses the frequency deviation, which is multiplied by a droop coefficient ($1/R$) to introduce an instantaneous power droop compensation (P_d) to stabilize the frequency. The loop of the governor closes through a first-order lag transfer function F_g,

$$F_g = \frac{1}{1 + T_g \cdot s} \tag{2}$$

where T_g is the time constant of the governor controller. The output of the governor controller is a regulation signal (ΔP_{valve}) that controls the turbine valves to regulate the mechanical torque T_m or mechanical power P_m of the generator.

After the resistance of the rotational inertia against frequency deviations, the governor as a primary controller is responsible to support the frequency during the initial stage of an event (from few milliseconds to several seconds). Then, if the system inertia does not return to its nominal value, a secondary level Automatic Generator Controller (AGC) is responsible for restoring the system frequency to the nominal value (e.g., 50Hz) by coordinating the signal P_o that is fed to the governor according to the scheduled power for each generator (P_{sc}), the system frequency, and the power flow in tie-lines (ΔP_{tie}). According to [5], [7], this controller can be developed based on a simple integral controller (K/s) running with a slower sampling rate compared to the governor controller, to decouple the dynamics of the two controllers.

B. Frequency support by distributed resources

As the penetration of RESs is increasing in modern power system, the inertia is reducing, as already explained in Section I, threatening the stability of the system. Therefore, it is highly important to enhance the resources that can provide frequency

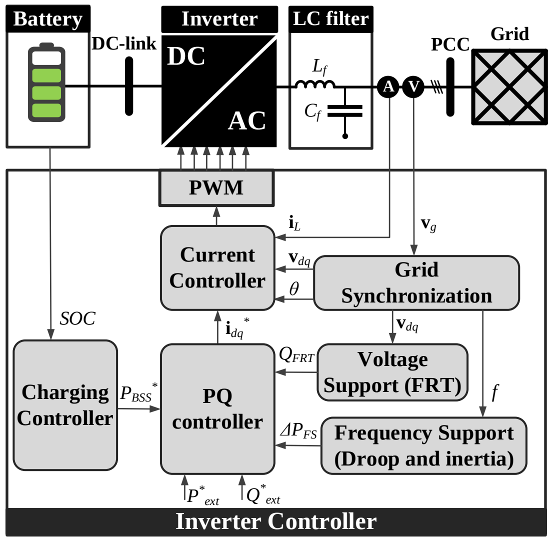

Fig. 3. A grid-connected DER with the structure of the inverter controller.

support services to the grid. Since DERs based on RESs usually operate at their maximum available power generation point according to the weather conditions, they are unable to provide upward power flexibility. However, inverter-based DERs equipped with ESSs are flexible devices that can provide upward flexibility and can support the frequency when it is needed. This support is enabled by introducing additional functionalities in the inverter controller of DERs.

A grid-following inverter controller, as shown in Fig. 3 is based on: a synchronization unit, a current controller, an active and reactive power (PQ) controller, a charging controller, and a voltage and frequency support units. A synchronization scheme [8] is responsible to estimate the phase angle (θ) of the grid voltage vector ($\mathbf{v}_g$) to enable the proper injection of the produced power to the grid in a synchronized manner. A current controller [10] ensures the accurate current injection according to the reference currents ($\mathbf{i}_{dq}^*$) provided by the PQ controller. The PQ controller [10] is responsible to manage the overall operation of the DER considering the priority of each operational mode. The voltage support unit has the highest priority when a voltage sag event occurs, in order to enable the Fault Ride Through (FRT) operation of the inverter and support the grid voltage by regulating the reactive power (Q_{FRT}) injection. A lower-level priority is given to frequency support services when a frequency disturbance occurs by regulating the active power injection according to (ΔP_{FS}), while under normal grid conditions the DER is operating either according to an internal charging controller or according to external power set-points (P_{ext}^* and Q_{ext}^*) provided by third party applications.

The frequency support scheme is the additional unit that is needed in the inverter controller to enable the provision of frequency support services by DERs based on ESS. This support service is enabled by adding an extra software function in the inverter controller to allow DERs to mimic the behavior of synchronous generators during frequency deviations. The support function aims to facilitate the droop control behavior and/or to emulate the inertia response by adding a virtual inertia. The droop control is emulated by considering a proportional regulation of the active power for frequency support (ΔP_{FS}) according to frequency deviation (Δf), while the virtual inertia response is synthesized by regulating ΔP_{FS} according the time derivative of the frequency, according to (3),

$$\Delta P_{FS} = k_f \cdot \Delta f + k_{vi} \cdot \frac{df}{dt} \quad (3)$$

where k_f and k_{vi} correspond to the coefficients that define the intensity of the droop control and the virtual inertia support, respectively. It is noted that if $k_f = 0$, then the droop support functionality is deactivated and, similarly, if $k_{vi} = 0$ the virtual inertia response is deactivated. The output of the support function (ΔP_{FS}) is added to the pre-fault operating conditions regarding the active power of the DER to provide frequency support services. The support provision is enabled when the frequency exceeds an upper (f_H) or a lower (f_L) frequency bound indicating the occurrence of a frequency disturbance.

III. Frequency Support through 5G Communication

Typically, the frequency support services are provided by conventional generation plants, while in modern power systems the concept of providing support by large-scale DERs is currently introduced, as explained in the previous section. In these cases, the support is provided according to local controllers that can rapidly respond to a frequency deviation without requiring any communication infrastructure. However, the deployment of an advanced measuring infrastructure in modern power systems based on synchrophasor technology, as well as the recent development of the 5G communication infrastructure, allow for the exploration of a new frequency support scheme that considers a wide area approach where any scale DER (under 5G communication coverage) can be coordinated to provide improved frequency support services. A new WAC-based scheme for coordinating DERs to provide fast frequency support through 5G communication is proposed in this work. This new WAC-based scheme is a centralized controller for fast frequency support based on: a Phasor Data Concentrator (PDC), a WAC activation with a power imbalance calculator, and a DER coordination unit.

A. Phasor data concetrator

A PDC unit is used to receive power injection measurements from the PMUs that are installed at power substations of the transmission system. It should be mentioned, that for this particular wide area scheme, only power injection measurements from generation or load buses are needed. Each PMU is able to measure and send the operating conditions of a corresponding substation with a fast reporting rate (e.g., 10 or 20 ms), while each measurement is time-stamped according to the Global Positions System (GPS) clock. These measurements are transmitted to the operator control center, where the WAC scheme is running, through 5G wireless communication according to the IEEE C37-118 protocol. Therefore, a PDC unit is developed in the WAC scheme to receive and time-align the PMU measurements received from the power system. As a result, at every control step (e.g., every 20 ms), the PDC is able to create a dataset which contains all power injection measurements that have been captured at the same time.

B. WAC activation with a power imbalance calculator

The power injection dataset is used by the power imbalance calculator to identify intense power imbalances that may initiate a frequency disturbance. For estimating the power imbalance at each wide area control step t (e.g., 20 ms), the total net power of the system at time t (P_{net}^t) needs first to be calculated according to the difference between the total generation and the total demand of the system, as given by,

$$P_{net}^t = \sum_{i \in \mathcal{B}^G} P_i^t - \sum_{j \in \mathcal{B}^L} P_j^t - \sum_{k \in DERs} P_k^t \quad (4)$$

where P_i^t corresponds to the power injection measurement at time t received by all buses that belong to the generation bus set $\mathcal{B}^G$ of the power system under consideration. Similarly, P_j^t represents the power absorption measurement from all load buses within the $\mathcal{B}^L$ set. Finally, P_k^t corresponds to the power injection of each flexible resource that is included in the set of $DERs$ that are participating in this WAC scheme. It is noted that each DER is connected under a load or generation bus and its operation is already captured within either P_i^t or P_j^t. Therefore, the third term of (4) is required for excluding the response of DERs coordinated by the WAC scheme in order not to consider the DER reaction as a new disturbance in the system. It should be mentioned, that synchronized measurements regarding the power injection of DERs participating in the WAC scheme are also required for this implementation.

Then, the system-level power imbalance identified at each time step (ΔP_i^t) can be calculated by the difference between two consecutive total net power calculations, according to,

$$\Delta P_i^t = P_{net}^t - P_{net}^{t-1} \quad (5)$$

The signal ΔP_i^t is actually the power imbalance that disturbs the swing equation (as described in (1)), causing a frequency deviation event. A negative ΔP_i^t indicates a loss of generation while a positive ΔP_i^t corresponds to a loss of load event. As a result, if ΔP_i^t exceeds a maximum power imbalance threshold ($\pm \Delta P_m$), then the WAC is activated since a significant power imbalance, capable of causing a severe frequency event (fault), is identified. When the WAC is activated, the P_{net}^{t-1} value is stored as the before the fault net power conditions P_{bf} , while the total power imbalance identified (ΔP_i) for the specific event is calculated as the maximum value between the P_{net}^t (for t after the fault) and the P_{bf}, as given by,

$$\Delta P_i = max\left(\left|P_{net}^t - P_{bf}\right|, \left|\Delta P_i\right|\right) \quad (6)$$

According to (6), if the power imbalance is evolving in the same direction, the identified ΔP_i will be updated and will track the maximum intense power imbalance for the system, which correspond to a critical frequency event. The WAC is activated for a specific time duration ΔT_f for each fault, and after this time duration the coordination signal for DERs will return to the pre-fault conditions, considering a ramping rate to allow for the smooth restoration of the system. It is noted that in case the WAC is activated and the ΔP_i^t violates the threshold in the reverse direction, the WAC scheme should be reactivated considering a new event.

C. DER coordination

The early-stage identification of the power imbalance ΔP_i is a key feature of the proposed WAC and it is used to coordinate DER response to take preventing action before the frequency disturbance is observed. In case of loss of generation event ($\Delta P_i < 0$), an upward power regulation is required by DERs, while for a load loss disturbance ($\Delta P_i > 0$) a downward flexibility is needed.

At every control loop (at time t), the WAC is aware about the upward $\overline{P}_k^t$ and the downward $\underline{P}_k^t$ availability of each DER k that is participating in the wide area frequency support

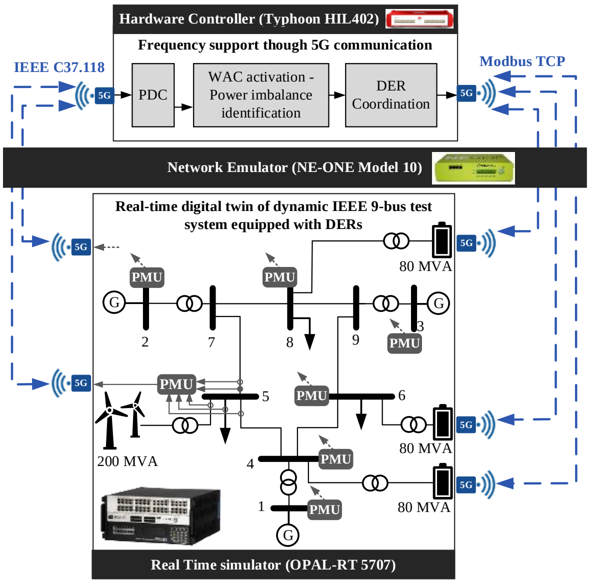

Fig. 4. HIL setup to demonstrated the proposed WAC scheme integrated through 5G communication for coordinating the frequency support by DERs.

scheme. Therefore, the total power imbalance identified for a severe generation loss event is allocated as a reference coordination signal to each DER k participating in this scheme, according to (7),

$$\Delta P_k^{t*} = \frac{\bar{P}_k^t}{\sum_{k \in DERs} \bar{P}_k^t} \Delta P_i \tag{7}$$

where ΔP_k^{t*} is the coordination set-point for DER k at each control step t. In case $\Delta P_k^{t*} > \bar{P}_k^t$, then ΔP_k^{t*} is limited to $\bar{P}_k^t$ to avoid any violation of the DER rating power. Similarly, when a severe load loss event is detected, then a corresponding coordination signal is generated according to the downward availability of DERs.

The coordination signals ΔP_k^{t*} are send to the DERs through the 5G communication infrastructure to timely prevent a frequency disturbance. It is highlighted that if the communication infrastructure is not adequate (fast and robust), then communication delay will decelerate the preventing response by the DERs minimizing the impact of the frequency support services coordinated by the WAC. Therefore, the communication delays are a crucial network performance that can affect the performance of the proposed WAC scheme that is integrated through the wireless communication infrastructure. The proposed WAC scheme is briefly presented in Fig. 4, where the concentration of PMU measurements and the coordination of DER over 5G communication infrastructure is also demonstrated.

IV. Demonstration of Use Cases

A. System description and experimental setup

An advanced experimental setup is developed to investigate the frequency stability of a power system according to different frequency support approaches. The experimental setup is developed by integrating a real-time digital twin of a power system with a network emulator and a digital controller in a HIL configuration.

An Electro-Magnetic Transient (EMT) model of a dynamic IEEE 9 bus test system is developed considering three generators equipped with local exciter and governor controllers according to [6]. The model is initially developed

Table 1. Design parameters of the power system digital twin

System	Parameters
Generators characteristics	G1: P_n=270 MVA, H=2.06 s; G2: P_n=270 MVA, H=2.06 s, *G3:* P_n=100 MVA, H=2.49 s
Governor controllers	Common sampling rate = 100 us, G1: T_g=0.1, R=0.05; G2: T_g=0.1, R=0.05; G3: T_g=0.09, R=0.05
AGC	Common sampling rate = 200 ms for G1-G3 Common integral gain K = 10 for G1-G3
DER inverter for ESS	Each site consists of 2 x 40 MVA ESS S_n=40 MVA, V_n=11 kV, f_n=50 Hz
Inverter controller	Controller sampling rate = 100 us Synchronization [8]: k_p=92, T_i=0.000235 Current controller [10]: k_p=1.05, k_i=90.91 Droop [10]: k_f=0.4S_n (MW/Hz) Virtual Inertia [10]: k_{vi}=H_{vi}·S_n/f_n, H_{vi}=2 s

in MATLAB/Simulink and proper modifications have been applied according to the Artemis Library modules to run in a real time simulator (OPAL-RT 5707) as a real time digital twin of a power system. In this power system, wind farms, virtual PMUs and inverter-based DERs [10] are added as shown in Fig. 4 to emulate the operation of a modern low-inertia system. The DERs included in the power system digital twin can be configured either not to respond to frequency deviations or to provide frequency support according to local controllers (Section II.B) based on droop and virtual inertia or to provide fast frequency support services according to external signals that are coordinated by the proposed WAC scheme (Section III). All the design parameters of the power system digital twin are presented in Table 1.

The proposed WAC scheme is digitally developed in a hardware controller (Typhoon HIL-402) as shown in Fig. 4 in order to meet the strict time requirements of such a wide area application for frequency support. The sampling rate of the WAC is 20 ms and in each control loop, the WAC scheme receives PMU measurements from the virtual PMUs of the digital twin using the IEEE C37-188 protocol. The WAC has also a bidirectional communication with the DERs participating in the scheme to monitor the upward/downward availability in each control step and to send the coordination set-points through Modbus TCP protocol.

The WAC is developed by considering a wireless communication to enable the wide area exchange of data. The wireless communication (e.g., 5G, 4G, etc.) is integrated in the experimental setup by incorporating a network emulator (NE-ONE Model 10) in the loop between the power system digital twin and the digital controller (WAC), as presented in Fig. 4. Through the network emulator, the performance of a wireless or a wire-based communication infrastructure can be configured to evaluate how the communication response can affect the power domain operation.

B. Results with no support, local support, WAC support

The advanced experimental HIL setup is used to enable the performance comparison between different control approaches to enhance the frequency stability of the system and under different communication networks. For all scenarios demonstrated in this work, a severe power imbalance is introduced, by losing 200 MW of wind generation at bus 5 at t = 30 s, which initiates a severe frequency event. In Fig. 5 - Fig. 8, the following signals are presented: the identified power imbalanced ΔP_i (excluding the DERs behavior), the total active power support by all the DERs (P_{DER}), the total power imbalance outcome ΔP_o when

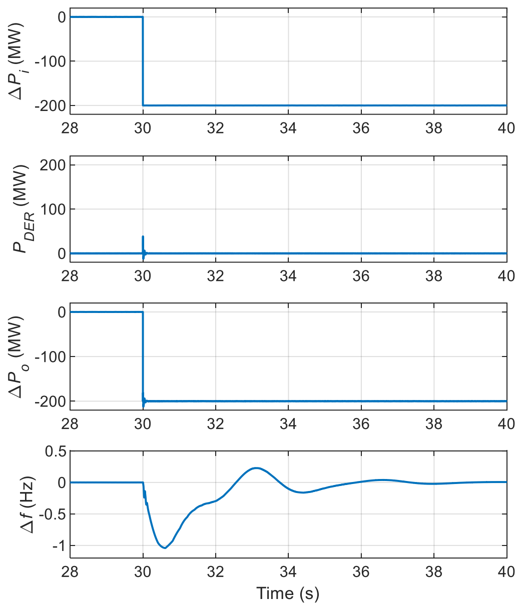

Fig. 5. Power system performance with no frequency support by DERs.

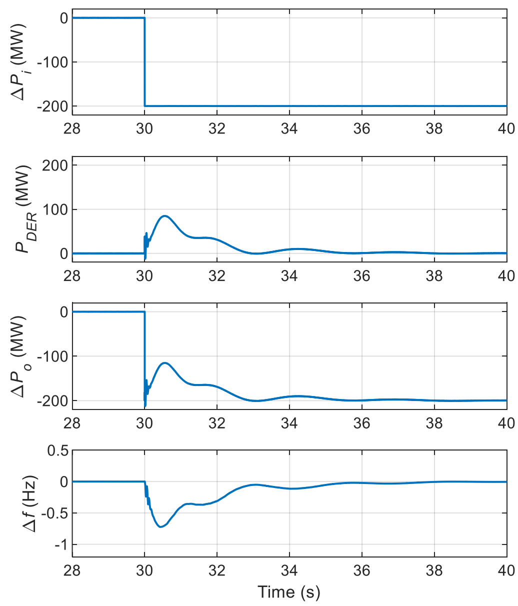

Fig. 6. Power system performance when DERs provide frequency support according to local control scheme based on droop and virtual inertial.

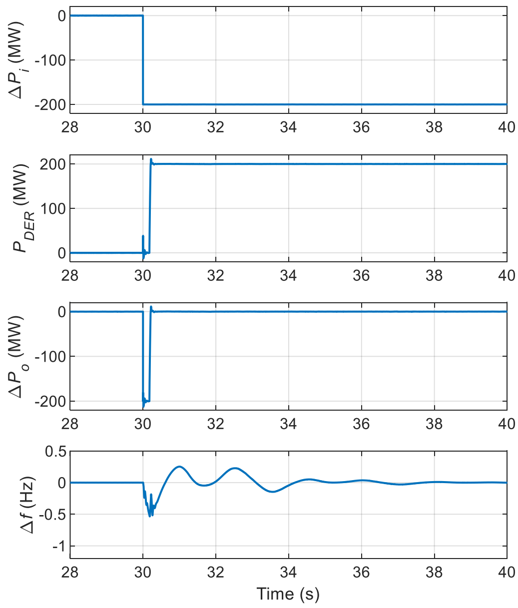

Fig. 7. Power system performance when the WAC scheme is integrated with a moderate 4G comminication network with an average delay of 50 ms.

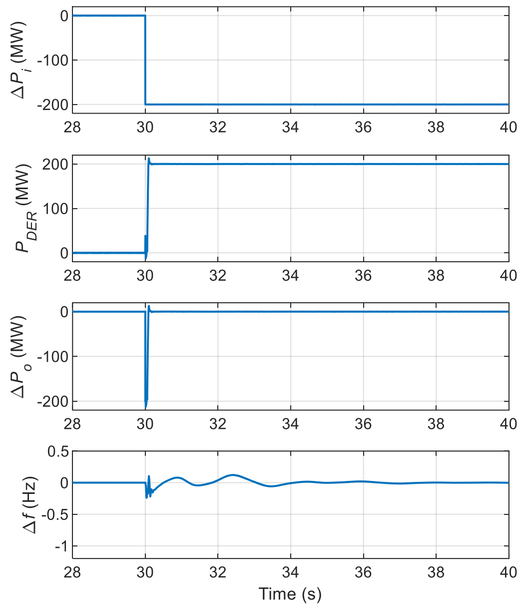

Fig. 8. Power system performance when the WAC scheme is integrated with a moderate 5G comminication network with an average delay of 10 ms.

DER behavior is included, and the system frequency response. Nine different scenarios have been performed for: no frequency support by DER (scenario #1), local DER support (scenarios #2 and #3), and DER support according to the WAC scheme under different communication network performance (scenarios #4 - #9), as summarized in Table 2.

The first scenario (scenario #1) is presented in Fig. 5 demonstrating the power system behavior when no frequency support is provided by flexible DERs. In this case, only the conventional generators are providing frequency support according to the governor and the AGC controller. A power imbalance of 200 MW initiates a severe frequency sag that threatens the system stability and a 48.96 Hz frequency nadir (minimum frequency) is observed in this baseline scenario.

The next scenario demonstrated in Fig. 6 (scenario #3) is related to the system response when DERs are also participating in the frequency support according to a local control scheme considering droop and virtual inertia capabilities. In this scenario, it is obvious that the provision of local droop and virtual inertia frequency services by DERs can improve the system stability. The observed frequency nadir is equal to 49.28 Hz in this scenario, improving by 31% the system frequency stability compared to the baseline scenario.

The following scenarios present the performance of the proposed WAC scheme when 4G (Fig. 7) or 5G (Fig. 8) communication is used for the wide area data exchange. The behavior of the WAC scheme in Fig. 7 (scenario # 5) considers a 4G communication where a 50 ms mean delay is configured by the network emulator according to a Gaussian distribution. Similarly, the result in Fig. 8 (scenario #7) presents the WAC performance according to a 5G communication with a mean delay of 10 ms. The fast communication and reduced delay (e.g., 10 ms) for the data exchange of the 5G scenario enables the DERs to take preventing actions according to the proposed WAC scheme to minimize the frequency disturbance as soon as the disturbance is initiated (power imbalance is detected).

Table 2. Stability benchmarking for different control and communication

#	Scenario	Stability performance indicators		
		f_{nadir} (Hz)	$RoCoF_{0.5s}$ (Hz/s)	$RoCoF_{0.2s}$ (Hz/s)
1	No support by DER (baseline)	48.96	-2.01	-2.85
2	DER with droop support	49.22	-1.54	-2.54
3	DER with droop and virtual inertia	49.28	-1.43	-2.46
4	WAC-FFR with 3G (100ms)	49.22	-0.75	-2.86
5	WAC-FFR with 4G (50ms)	49.46	-0.28	-2.09
6	WAC-FFR with 4G (20ms)	49.65	-0.07	-1.03
7	WAC-FFR with 5G (10ms)	49.76	0.03	-0.70
8	WAC-FFR with 5G (3ms)	49.76	0.02	-0.35
9	WAC-FFR with ideal comm.	49.80	0.08	0.04

In this case, the frequency nadir increases to 49.76 Hz, demonstrating a 77% improvement compared to the baseline scenario #1 where the frequency support is only provided by conventional generators, and a 69% improvement compared to scenario #3 where both generators and DERs are providing frequency support according to a local control scheme. As it is demonstrated by this scenario, the proposed WAC scheme for fast frequency support can achieve an outstanding performance regarding frequency stability. The results in Fig. 7, for the WAC performance according to 4G, indicates that the additional communication delay (compared to the 5G case) decelerates the WAC response and reduces the effectiveness of the proposed scheme.

Table 2 summarizes all the results to enable a benchmark regarding the frequency stability when local frequency support is provided by either the generators only or the generators and DERs, and when the WAC scheme is utilized to support the system considering different communication infrastructures. Benchmarking is facilitated by using three key performance indicators for the frequency stability of the system; the frequency nadir which represents the minimum frequency during the disturbance and two indicators regarding the rate of change of frequency, $RoCoF_{0.5s}$ and $RoCoF_{0.2s}$, which have been calculated as the average *RoCoF* calculated for the first 500ms and 200ms, after the disturbance is initiated, respectively. It is obvious that by introducing local controller to DERs for frequency support (scenarios #2 and #3), the frequency stability is improved (by 25-31%) and a higher frequency nadir and lower *RoCoF* is achieved compared to the baseline scenario #1 where only generators are supporting the frequency. The consideration of virtual inertia (scenario #3) can achieve a slightly better performance compared to the droop only approach.

On the other hand, when the frequency support is provided by DERs according to the proposed WAC scheme instead of the local controller (scenarios #4 - #9), then it is observed that the communication performance can significantly affect the system performance. In these scenarios, a different communication is used (e.g., 5G, 4G, 3G) considering different mean delays [17]. When 3G communication is used in WAC, the stability is almost equivalent with the local support approach, while in case of 4G communication an improvement of 25-52% can be achieved when a communication delay is between 20 and 50 ms. Furthermore, when a 5G communication infrastructure is used, with a 3 to 10 ms of delay, then an almost 70% improvement can be achieved, compared to DERs with local control approaches, in frequency nadir, while a significant reduction of RoCoF is also achieved. The performance of the WAC in the case of 5G is almost equivalent to the performance in case of ideal communication, indicating the importance of incorporating 5G communication in such WAC applications.

V. Conclusion

This work focuses on enhancing the frequency stability of the power system by introducing a WAC that can be integrated through 5G communication, enabling the participation of DERs without requiring wire-based communication. The WAC timely identifies power imbalances and coordinates DERs to take preventing actions and enhance system stability. Benchmarking is performed based on an advanced HIL, showing that the proposed WAC can significantly enhance system stability as compared to scenarios where DERs provide frequency support according to local controllers. In addition, among different wireless communication technologies, only 5G is capable to ensure the proper performance by the WAC to significantly enhance stability.

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