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NOTICE

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Abstract— **Distributed energy resources (DERs) providing frequency regulation is a promising technology for future grid operation. Unlike conventional generators, DERs can use open communication networks to exchange signals with control centers, possibly through DER aggregators; therefore, the impacts of communication variations, including latency, on the system frequency stability need to be investigated. This paper develops a cyber-physical dynamic simulation model based on the Hierarchical Engine for Large-Scale Co-Simulation (HELICS) framework to evaluate the impact of communication variations, such as delays in DER frequency regulation. The feasible delay range can be obtained under different automatic generation control (AGC) parameter settings. The results show that the risk of instability generally increases with the communication delay and that the different impacts of delays in the AGC provided from DERs and conventional generation units should be recognized when designing frequency regulation controllers.**

Keywords—automatic generation control, cyber-physical, communication delay, dynamic simulation, distributed energy resources.

I. INTRODUCTION

With the rapid deployment of distributed energy resources (DERs), including flexible loads and smart buildings [1], their capability to provide frequency regulation is being investigated [2], [3]. Frequency regulation for power systems is commonly referred to as load frequency control (LFC). LFC includes primary frequency regulation (PFR), which is provided by each generating unit in a distributed manner, usually through a droop control; and secondary frequency regulation (SFR), which originates at a central controller in the system operator's control room and adjusts the generation set points [4]. This paper studies the impact of delays in controlling DERs for SFR. Note that this paper uses SFR and automatic generation control (AGC) interchangeably.

Unlike conventional generators, which use a dedicated communication channel to provide AGC [4], DERs can use open communication networks to exchange control signals with system control centers, possibly through DER aggregators [5]. The open networks expose several vulnerabilities of the DER AGC services, such as extended communication latency, increased packet loss, and cyberattacks (e.g., false data injection); therefore, it is imperative to study the impact of the communication variations in DER AGC on the system frequency stability to ensure reliable grid operation of the future electric grid with high penetrations of DERs. Although it depends on the specific communication infrastructure, normal time delays—ranging from several tens to hundreds of

milliseconds—are introduced in transmitting and processing remote signals [6], [7]. These delays will likely increase when open communication networks (e.g., mobile or fixed broadband) and multilayer structures (DER aggregators) are introduced, especially during periods of congested communication because of the large amount of data exchange.

Existing research on the communication delay in LFC focuses on conventional generators. Reference [8] designs a delay-dependent LFC (to find the parameters for proportional integral [PI] controllers) for time-delay power systems. In [9] and [10], linear matrix inequalities are used as a stability criteria to design PI controllers and to find the delay margin of the system, respectively. Reference [11] discusses the impact of a transmission delay and the sampled control signal on the system stability because the AGC signals are updated every few seconds in the field. Reference [12] investigates the impact of the discrete secondary controllers on the dynamic response of power systems and discusses the analogy between AGC and real-time electricity markets.

The existing research studying AGC with delays and system frequency stability is based on traditional modeling of the state-space representation and Lyaponuv theory for AGC and an aggregate manner of simulation (e.g., total inertia in Simulink) with rather simplified test systems. Further, the current delay margin evaluation methodology might not be well suited for DER AGC control analysis with multilayer open communication networks and discrete control signals.

This paper develops a cyber-physical dynamic simulation (CPDS) model to study the impact of the communication delay on DER AGC and system frequency stability. This model can be considered an agent-based modeling scheme, in which the interactive/collective and internal behaviors of different agents (e.g., transmission, DER aggregators) are modeled through a co-simulation environment and in a disaggregated manner. Agent-based modeling provides the benefit of simulating heterogeneous interactions among agents [13]—for example, different delays and response times of conventional generation and DERs. The discrete AGC control signal is sent from the system control center to DER aggregators every 4 seconds. The DER dynamic response and system frequency response are modeled in ANDES, which is an open-source, dynamic simulation tool [14]. The combined CPDS co-simulation model is built in the Hierarchical Engine for Large-Scale Co-Simulation (HELICS). Then, the feasible space of the communication delay is obtained through a heuristic search with multiple simulations with the proposed model.

The rest of this paper is organized as follows: Section II introduces DER dynamic and LFC models with delays. Section

1

III develops the co-simulation model and framework in HELICS. Section IV presents the case study to demonstrate the impact of delays in DER AGC and the differences from traditional generation. Section V concludes the study.

II. DER Dynamic Model Including LFC Model with Communication delays
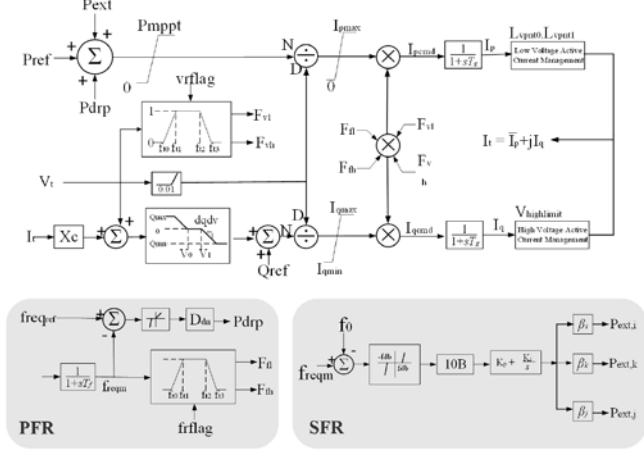

Fig. 1. DER frequency dyanmic model, PFR, and SFR.

A. DER Frequency Dynamic Model

Here, we modify the Western Electricity Coordinating Council PVD1 model [15] to represent DER frequency dynamic behavior, as shown in Fig. 1, from the device level. The maximum power point tracking (MPPT) model, which represents the maximum available power from distributed photovoltaics (PV), is added. Generic models of PFR and SFR for DERs are also included in the figure. Note that a variable representing the limit of the maximum available power from MPPT, P_{mppt}, has been added to the dynamic model. This allows the model to consider the PV production headroom or other user-defined limits. More details on the dynamic model can be found in [15].

1) PFR

PFR uses droop control: when the frequency drop is larger than a PFR deadband, the DER changes its active power output accordingly. An additional power output, P_{drp}, is added to the generation output:

$$P_{drp} = \begin{cases} \frac{(60-db_{UF})-f}{60} D_{dn}, f < 60 \\ \frac{f-(60+db_{OF})}{60} D_{dn}, f > 60 \end{cases} \quad (1)$$

where db_{UF} and db_{OF} are the underfrequency and overfrequency deadband; and D_{dn} is the per-unit power output change to 1-p.u. frequency change (frequency droop gain).

2) SFR

SFR is enabled by an AGC model that includes two components: an area-level estimation of the area control error (ACE) from (2) [16] and a plant-level control logic that receives the ACE signal and sets the SFR reference power, P_{ext}, for each

plant. For simplicity, it is assumed that there is one area in the simulation and no interchange with other areas:

$$ACE_{tt} = 10B(f_{reqm,tt} - f_0) \quad (2)$$

where tt is the AGC time interval index; ACE_{tt} is the ACE at the AGC interval tt; $f_{reqm,tt}$ is the measured system frequency at the AGC interval tt; f_0 is the system reference frequency (60 Hz); B is the frequency bias in MW/0.1 Hz; and f_{db} is the frequency error tolerance deadband.

As shown in Fig. 1, for the SFR, the PI control is applied to the ACE signal; K_P and K_I are the coefficients of the PI controller. The ACE signals are updated every 4 seconds to represent their discrete nature in the field. The output from the PI controller is then passed on to each AGC generator considering the unit's participation factor (β_i is the i-th unit's participation factor), resulting in the final control reference, $P_{ext,i}$. Note that the participation factor of each unit is decided by a real-time economic dispatch that is normally updated every 5 minutes. Each DER's participation factor can be updated by the DER aggregator as well as under a different time interval based on the local aggregator's optimization.
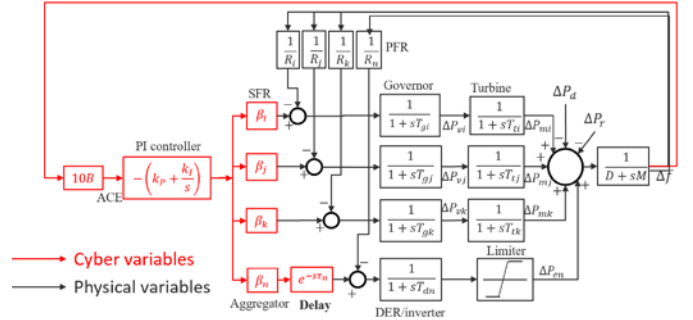

Fig. 2. Schematic model of the cyber variables (red) with delays and the physical parts in transmission (black).

B. LFC with Delays

LFC from DERs with delays is shown as a block diagram in Fig. 2. It combines PFR and SFR with added delay blocks from a system-wide perspective. The red lines and blocks represent the cyber variables where communications are required, whereas the black represents the physical variables (governors, turbines, inverters) and locally controlled PFR. This synthesis of LFC with delays can also be expressed as state-space equations analytically. First, define the following state and output vectors, as in (3) [10], [17]:

$$\begin{aligned} x(t) &= [\Delta f \quad \Delta P_m \quad \Delta P_v \quad \int ACE]^T \\ y(t) &= [ACE \quad \int ACE]^T \end{aligned} \quad (3)$$

where Δf is the system frequency deviation; ΔP_m is the conventional generator mechanical power deviation; ΔP_v is the valve/gate position change of the governor; and $\int ACE$ is the integral of ACE. The control signal with the PI controller is written as shown in (4):

$$u(t) = -K_P ACE - K_I \int ACE. \quad (4)$$

2

Therefore, the delayed LFC state-space equations are shown as in (5) [17]:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + A_d x(t - d(t)) \\ \qquad\qquad + B_h u(t - h(t)) + Fw(t) \\ y(t) = Cx(t) \end{cases} \qquad (5)$$

where $d(t)$ and $h(t)$ are the time-varying delay amounts in the state and control input vectors; $w(t)$ is the system disturbance (e.g., load or generation change); A, B, C, which are normally assumed to be known, are the state matrix, control matrix, and output matrix, respectively; F is the perturbation matrix; and A_d and B_h are the state matrix and control matrix but describe the relationship with the previous state and control vectors. For example, the previously calculated control vector, $u(t - h(t))$, affects the current state, $x(t)$. Note that because the PI controller is included in (5), it is also called a static output feedback control problem (K_P, K_I are constants) [17]. In this paper, (5) serves as the exposition of the delayed control system.

III. CPDS CO-SIMULATION

This section develops the proposed CPDS co-simulation for studying delay impacts in DER AGC. This co-simulation is based on the HELICS platform and the open-source power system simulator ANDES. HELICS is an open-source, cyber-physical co-simulation framework for energy systems. Following are a few key concepts of HELICS that are relevant here; for more details, see [18]:

- *Federates* are running simulation instances of individual subsystems, sending and receiving physical and control signals to and from other federates.

- *Brokers* maintain synchronization in the federation (i.e., many federates) and facilitate information exchange among federates.

- *Simulators* are executable—that is, they can perform some analysis functions. In this context, they are the transmission simulator ANDES and the defined control room and DER aggregator functions. Note that the terms *federate* and *simulator* are used interchangeably here.

- *Messages* are the information passed between federates during the execution of the co-simulation. The message exchange is realized through either defining subscriptions and publications functions or federate-to-federate end-point communications. Filter functions can be applied to end-point messaging.
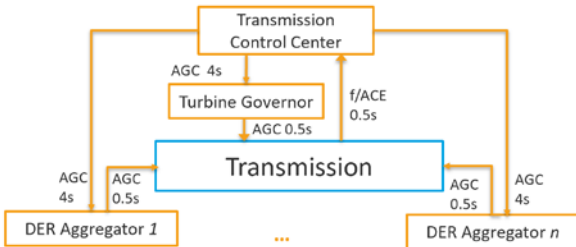

Fig. 3.   Simulation components with information exchange.

Assume that the overall system comprises a transmission system dynamic simulator; a control center; turbine governors of conventional generators; and a DER aggregator for each load bus, including distributed PV or other DERs, as shown in Fig. 3.

The transmission dynamic simulator sends the system frequency and the ACE signals to the transmission control center every 0.5 second, where the AGC signals are calculated with the PI controller and sent to the turbine governors and the DER aggregators every 4 seconds. This setup is modeled in HELICS, where the transmission dynamic simulation federate uses ANDES. The setup and the data exchange of the federation is shown in Fig. 4.
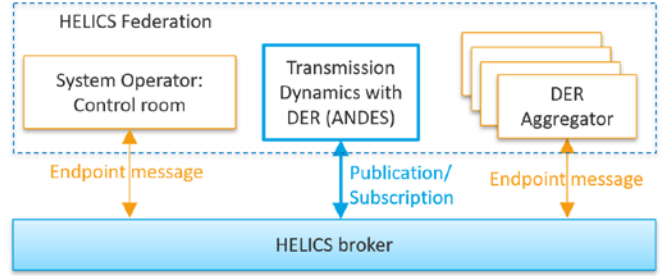

Fig. 4.   HELICS federation setup.

IV. TEST SYSTEM AND CASE STUDIES

The IEEE 39-bus system shown in Fig. 5 is used to evaluate the impact of the communication delay on the DER AGC signals. In this study, distributed PV is used to represent the DERs. Other DERs can be added as well. Assume the following system operating condition: 40 DERs at every load bus, for a total of 19 load buses with 760 DERs; the generation of the DERs is 20% of the loads at every load bus, and they are distributed evenly. The DER frequency dynamics with PFR and SFR have been added in ANDES, as described in Section II.
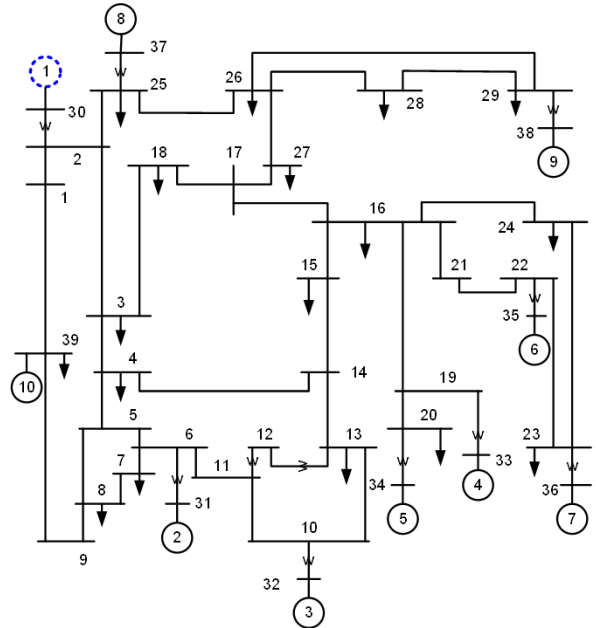

Fig. 5.   IEEE 39-bus transmission test system.

A generation outage at Bus 30 (marked in Fig. 5) is created at the 5th second. Fig. 6 shows the frequency dynamic response of the system, and Fig. 7 shows the DER AGC signals; both figures include various delay scenarios. One can observe that the 4-second delay causes system instability, and thus the delay margin is between 3 and 4 seconds in this setup (k_P=0.2, k_I=0.2). Note that in open networks, if multiple delays are included (e.g., communication/routing delay, congestion, latency, time needed for calculation), the total delay amount could be a few seconds or even longer [19], [20], [21]. This highlights the importance of considering delays when designing controllers, even more so with DERs and open communication networks.
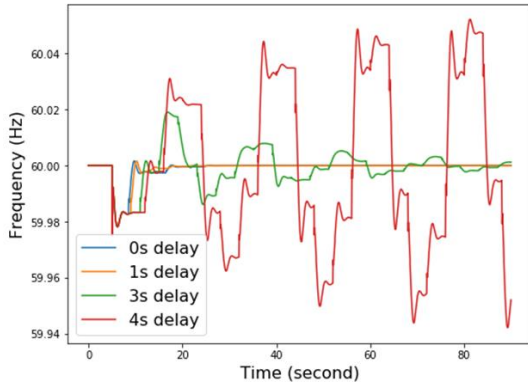

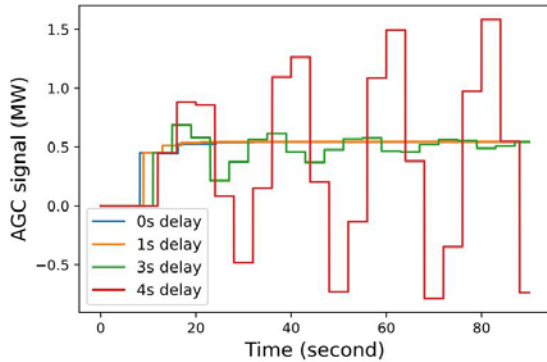Fig. 6. System frequency response under different DER delay signals.

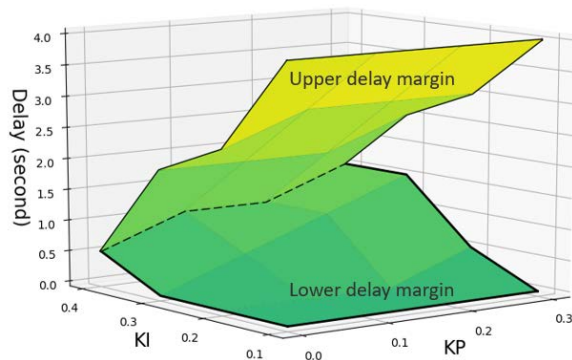Fig. 7. DER AGC signal under different communication delays.

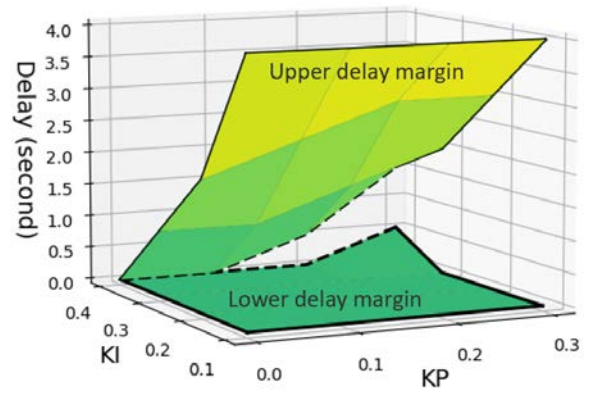Fig. 8. Feasible space of the three values in DER AGC controls.

Fig. 9. Feasible space of the three values in turbine governor AGC controls.

The delay margins for different PI controller parameters, k_P and k_I, are shown in Fig. 8 as a 3D plot; the enclosed space between two surfaces is the feasible space of the three values (k_P, k_I, and delay), ensuring the stability of the system. Fig. 9 also shows the feasible space but for conventional generators providing AGC scenarios. A comparison of the two figures shows that the upper and lower delay margins (surfaces) are quite different. In the DER case, when k_P, k_I are large, shorter delays can cause system instability, whereas longer delays do not. This is because large values of k_P and k_I tend to overcompensate the system ACE, though the delays can offset this overcompensation to some degree; see the lower delay margin at k_P=0.3, k_I=0.4 in Fig. 8. In the case of the conventional generators providing AGC, however, generally longer delays tend to have a higher risk of instability. This difference is because the response rate of the DERs (with inverters) is much faster than the traditional turbine governors. This demonstrates the different impacts of delays in AGC signals using DERs and traditional generation. Note that the simulated scenarios assume all the delays are the same, the scenarios with different delays will be included in future work.

V. CONCLUSION

This paper investigates the impacts of the delayed AGC signals of DERs on the frequency stability of the system. A scalable cyber-physical dynamic simulation model is developed based on the HELICS platform and an open-source transmission dynamic simulation tool, ANDES. The DER frequency dynamics are modeled in transmission simulations with delays. The simulation results with hundreds of DERs show that the risk of the system instability might substantially increase if the design of the DER AGC control fails to consider communication variations. The communication delay margin of DER AGC can be quite different from that of conventional generators; therefore, system operators should consider communication delays when designing DER AGC control parameters and when dispatching DERs for AGC services. Our future research will focus on theoretical analysis regarding the stability of the discrete AGC signal of DERs.

4

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