Inertia Emulation Control using Demand Response via 5G Communications

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Abstract— **Building energy equipment is moving rapidly towards Internet of Things (IoT)-driven devices to provide consumer connectivity and device management. These device-level interfaces along with 5G communications will be leveraged to develop control architectures to engage a large number of monitoring and control devices and provide real-time and reliable energy services. Emerging 5G networks have high potential to provide the communication technology for demand response, with fast transfer speed, high reliability, and high number of connections. Guaranteed inertial response to limit frequency fluctuations is one of the main challenges in modern power systems due to the increased penetration of renewable generation, and it is largely affected by communication delays and packet losses. This paper analyzes inertial response and rate of change of frequency in a power system model with inverter-interfaced air conditioners. The control loop considers time delays and packet losses to show the need to switch to 5G networks in future smart grids.**

I. INTRODUCTION

The electric grid that underlies our economy and daily lives is changing rapidly. The U.S. electric grid is evolving from an architecture of large, centralized power generation and control to a hybrid system that incorporates various distributed energy resources (DERs) near the load. High penetration of DERs, such as solar and wind, can result in unacceptable frequency excursions due to the deterioration of inertial response in the presence of disturbances. Utilizing response from the demand side as a synthetic inertial response can help reduce rate of change of frequency (RoCoF).

Utilizing demand control to provide grid services requires synchronized wide-area control of a significant number of loads (millions to tens of millions) to deliver a deterministic and necessary response to the electric grid needs. At the grid edge where consumers connect to the grid, vast sensor arrays, high-speed networks, and advanced communications create a dynamic space where energy is not only passively consumed but generated, stored, managed, and traded. The communication delays and packet losses in sensors and actuators are an important challenge for inertia emulation control in power systems with demand response (DR) [1], [2].

In [3] and [4], it was shown that residential loads could be intelligently controlled to provide frequency regulation services for power systems. The nonlinear behavior models of residential customers are considered in [5] to implement DR in a unit commitment of power systems [6]. In [7], [8], [9], [10], the authors show that thermostatically controlled loads are able to provide balancing services under the constraint of guaranteeing user comforts. Hence, using proper dispatching and modeling methods in DR programs can positively impact power systems reliability. However, communication delays, transmission errors, and packet losses are unavoidable [11] and proven to have a significant negative impact on the inertial response, in particular, a severe degradation of RoCoF [12]. Developing a new framework that accounts for the dynamics of the electric grid and grid-responsive loads would facilitate the scalable deployment of demand-side management technologies, which leverage the two-way communication to end-use devices for fine grained control. 5G networks have the potential to enable communication and control architectures by leveraging services with massive machine-type communications, ultra-reliable low-latency communications, and enhanced mobile broadband.

This paper investigates the effects of communication delays and packet losses on inertia emulation control in a power system with DR setting, where the demand load is represented by inverter-interfaced air conditioners (IACs) [13]. IACs are favorable to be controlled as demand side resources to provide operating reserve, as compared to regular air conditioners (ACs), since their compressor's operation frequency is adjustable. The simulation results show latency and packet loss range of effects on the inertial response of the

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system. The use of an improved communication technology, such as 5G, would allow new functionalities in future smart grids to improve their reliable operation.

This paper is organized as follows. Section II provides the preliminaries on 5G technology for demand response in smart grids. Section III describes the problem formulation by introducing the model of power system with DR. Section IV presents the simulation results of frequency regulation in the time scale of inertial response for a power system including IACs as a DR. Different scenarios representing different time delays and packet losses are considered to analyze their effects on the inertial response of the system. Finally, Section V provides the conclusion.

II. 5G Technology for Demand Response

Networked control systems (NCS) such as smart grids are spatially distributed systems in which the communication between sensors, actuators, and controllers occurs through a shared band-limited digital communication network [14]. This system structure requires ensuring data packets to be successfully transmitted between the control components to ensure the reliability of such NCS. Addressing the network-induced delays and packet dropouts in NCS, a scalable and pervasive communication infrastructure is crucial in both the construction and operation of a smart grid [15].

In the past few years, the 5G network is being promoted widely across the world due to its advantages in transfer speed, reliability, security, power consumption, and large number of connections [16]. Hence, utilizing the 5G network can help achieve fast transfer speed, low communication latency, high security, and a massive number of connections in future smart grids [6]. The critical improvement in this network communication is in transfer capacity, energy efficiency, and interference management. These features can be achieved using 5G network as an ultra-dense cellular network, where 5G base stations are anticipated to be 40–50 (BS/km^2) as compared to 4G network base stations that are close to 8–10 (BS/km^2) [6]. The 5G massive multiple-input multiple-output (MIMO) antennas are similar to existing 3G and 4G base station antennas, but with a significantly higher frequency and beam-steering and beam-forming technologies that help the 5G base station antennas to direct the radio signal to the users and devices rather than in all directions [17], see Fig. 1. Moreover, robust security and high reliability are other achievements of using 5G networks. The 5G network architecture can enhance data transfer security and support diversified services via end-to-end service level agreement assurance [6]. The 5G network slices are separated from each other and can be regarded as individual structures managed in the core network [18]. For the 5G network, the core network is being redesigned to better integrate with the Internet and cloud-based services, and it also includes distributed servers across the network that improve response times and reduce latencies [17].

In general, the DR aggregator may receive the area control error (ACE) or other defined control error for the system and send control signals to users to adjust their power consumption and provide regulation power [6]. However, due to the network bandwidth limits and network traffic congestion, usually, network-induced delays and packet dropouts are unavoidable [14]. In this case, the system frequency regulation as one of the critical regulatory processes will become unstable when the communication delay time is over 0.4–0.5 s [19], [20]. The significant advantages of 5G network make it an application potential for DR in smart grids. In this framework, the massive machine-type communications' feature of 5G network allows to achieve large numbers of communication links among different loads that provide more accurate and applicable demand response control [6], [21]. Moreover, the fast transfer speeds and low communication latencies in 5G networks for remote control allow DR aggregators to send and receive information signal with an acceptable delay and packet loss where the delay time can decrease to 1 ms.

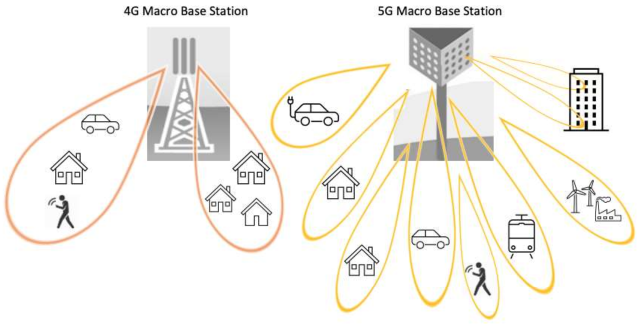

Fig. 1. The 4G base station with sector antennas and the 5G base station with multi-element massive MIMO antenna array

This paper shows the effects of time delays and packet losses in inertia emulation and RoCoF control using demand response as a part of frequency regulation. The primary aim is to show the need for 5G networks in future smart grids, where low communication delays and low probability of packet losses lead to accurate frequency regulation.

III. Problem Formulation

In this section, inertia emulation control in a power system model with IACs is considered to analyze the effects of communication delays and packet losses [13]. The general structure of the power system with IACs is illustrated in Fig. 2, where the DR controller is connected to the IACs to provide the required amount of support to the grid. When a disturbance ΔP_L occurs, the system frequency changes. In systems with high levels of renewables, the frequency nadir and the RoCoF can exceed the nominal operational constraints. Thus, controlling the RoCoF and frequency nadir has a significant role in mitigating the impact of disturbances. RoCoF can be used as a key index for the control of frequency excursion [22], [23]. Generating units will regulate the power generation ΔP_G to recover the system frequency. However, when DR is considered in the power system, the DR controller can also receive the RoCoF ($\Delta \dot{f}$) and send control signals to the IACs to adjust their power

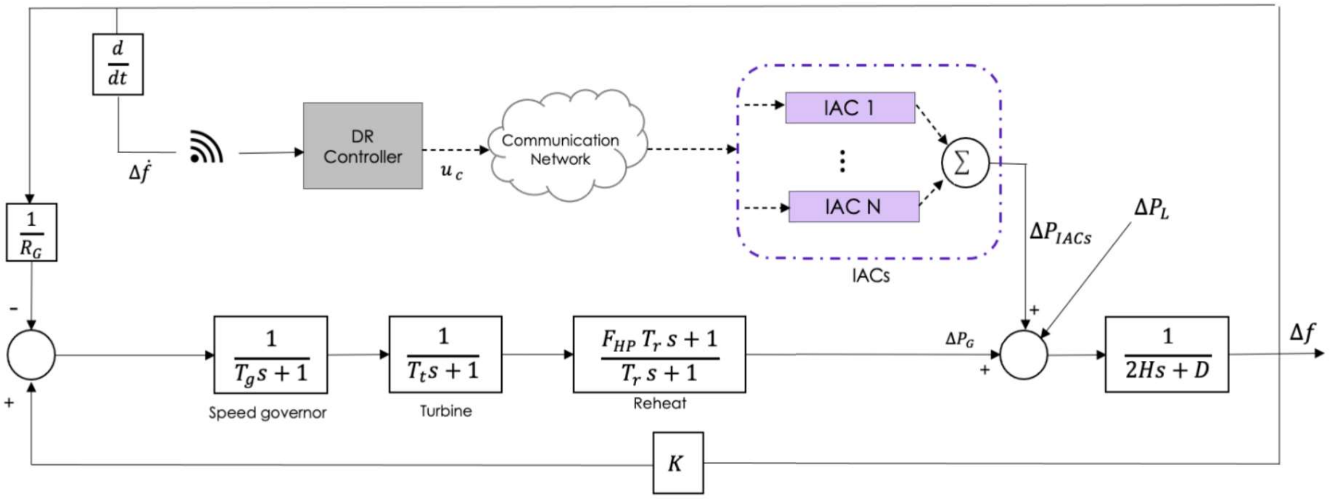

Fig. 2. Transfer function model of power system with IACs

consumption and provide regulation power ΔP_{IAC}. However, the measurement and data transfer of RoCoF and control signal (u_c) are subject to communication delays [24].

Considering IACs as the load demand that can be controlled by the DR controller, the frequency regulation capacity can be evaluated as:

$$\Delta f_{IACs}(s) = \frac{(1+T_c s)(1+C_i R_i s)DR(s)}{(1+T_c s)(1+C_i R_i s)+k_Q R_i C(s)}\Delta f(s) \quad (1)$$

where Δf represents the the power system's frequency deviation and Δf_{IACs} is the compressor's operating frequency deviation. Here, by considering the inertia emulation as the short time period of frequency regulation process, the outdoor temperature is assumed to be fixed, and there is no change to the setpoint temperature [3], [13]. C_i and R_i are the thermal capacity, and thermal resistance of room-i, T_c represents the inertia time constant of the compressor, and k_Q is the coefficient of the cooling capacity [13], [3]. The proportional-integral controller $C(s)$ has been verified to achieve the adjustment of the compressor's operating frequency [3]. The controller of the IACs providing regulation capacity for the power system is represented by $DR(s) = \delta + \frac{\gamma}{s}$ that is considered as a DR controller. The power consumption of the IACs can be described as:

$$P_{IACs} = \frac{K_p}{1+T_c s} f_{IACs}(s) + \mu_p \quad (2)$$

where K_p and μ_p are the coefficients of the power consumption. The IACs regulation capacity is expressed in (3), where in this framework it is connected to the primary model by $\Delta \dot{f}$ (RoCoF) to provide inertia emulation control [13].

$$\Delta P_{IACs} = \frac{K_p(1+C_i R_i s)}{(1+T_c s)(1+C_i R_i s)+k_Q R_i C(s)} DR(s)\Delta f(s) \quad (3)$$

Note that the regulation capacity provided by one IAC is small, so the aggregated regulation capacity of a large-scale IACs is generally considered in modeling and simulation [3], [13].

Based on the presented power system model with IACs in Fig. 2, the frequency deviation can be obtained by

$$(2Hs+D)\Delta f(s) = \Delta P_G + \Delta P_L + \Delta P_{IACs} \quad (4)$$

where D and H express the load damping and the inertia constant of the system, respectively [13]. The load deviation is represented by ΔP_L, and ΔP_G is the regulation power provided by the generator that can be described as:

$$\Delta P_G = \frac{(F_{HP} T_r s+1)}{(T_g s+1)(T_t s+1)(T_r s+1)}(K - \frac{1}{R_G})\Delta f(s) \quad (5)$$

where T_g, T_t, and T_r are the time constants of the speed governor, turbine, and reheating process, respectively. F_{HP} represents the high-pressure turbine constant, and R_G denotes the speed droop. Then, the RoCoF can be easily obtained by computing $\Delta \dot{f}$ and will be sent to the DR controller to provide the required regulation power for inertial response in the presence of disturbances.

In the provided model, the system frequency deviation is initially detected by the DR control center, and then a control signal will be sent to each IAC's controller to adjust the required regulation capacity. In this send and receive process, the communication delay ($e^{-\tau s}$) and packet loss can happen due to the network bandwidth limits and network traffic congestion. Here, it has been assumed that an actual delay and packet loss on the control signal (u_c) exist, and our comprehensive results are shown to validate the need for 5G networks in future smart grids.

IV. CASE STUDY

In the given model, the generator inertia H is set to 6 s and the load damping factor D to 1. The control parameters for the generator R_G and K_G are 0.1 and 0.5, respectively. For the DR controller ($DR(s)$), the parameters δ and γ are set to 200 and 0.02, respectively. Also, the time constants for the speed governor are selected as $T_g = 0.2$ s, $T_t = 0.3$ s, and $T_r = 7$ s. The simulation results for the power system model with IACs control loop and parameters given in [13] are presented

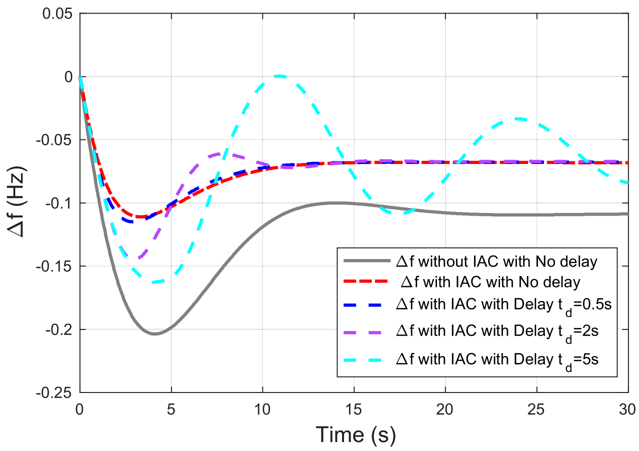

Fig. 3. The comparisons of inertial reponse for different time delays

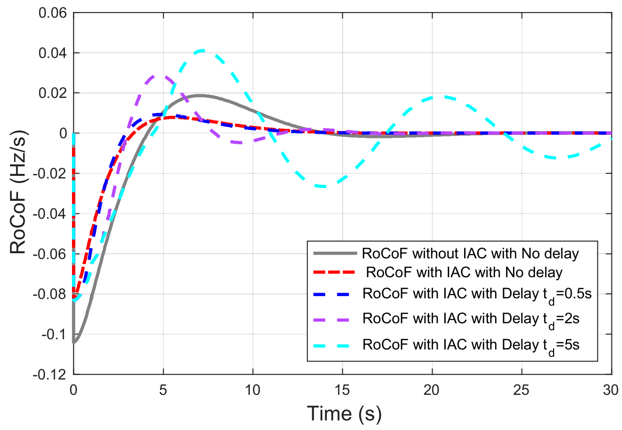

Fig. 4. The comparisons of RoCoF for different time delays

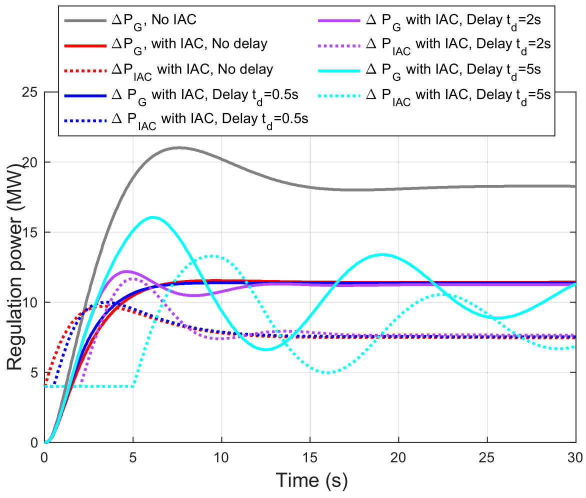

Fig. 5. The comparisons of regulation power for different time delays

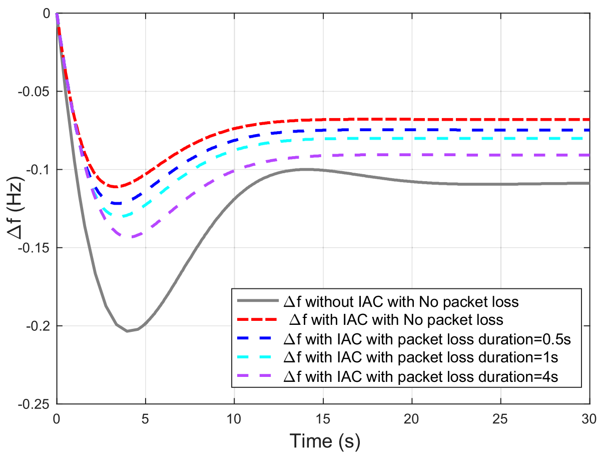

Fig. 6. The comparison of inertial response for different time durations of packet loss

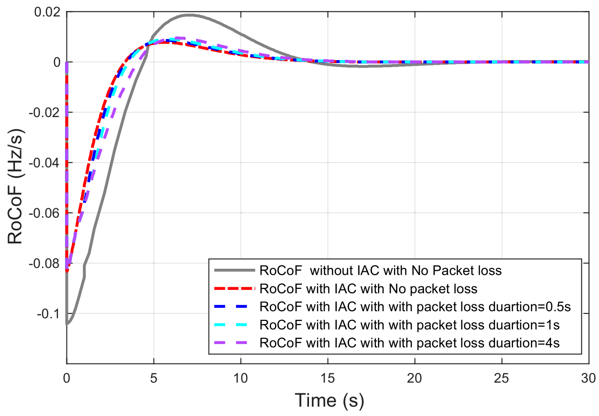

Fig. 7. The comparison of RoCoF for different time durations of packet loss

in this section with a disturbance of 20 MW step increase in load and a system capacity of 800 MW. Fig. 3 shows the frequency regulation for different communication delays in sending RoCoF signal, i.e., the derivative of frequency $\Delta\dot{f}$, to the DR controller. Clearly, increasing the delay lowers the frequency nadir and decreases the emulated inertia, and it could lead to instability of the system. The fluctuations of RoCoF using DR with IACs decrease as time progresses, and they are affected by the communication delays as seen in Fig. 4. Furthermore, Fig. 5 shows the regulation power in the inertial response time scale.

Fig. 6 shows the results for different packet loss durations in the RoCoF signal transmission. The packet loss starts at $t = 0.5$ s and is applied for different time durations. As the results show, losing data impacts the RoCoF and inertial emulation control as it it is clear in Fig. 6 and Fig. 7. Increasing the duration time of packet loss will lower the frequency nadir and decrease the emulated inertia provided by DR with IACs. Fig. 8 shows the impact of data losses on the regulation power. The presented results provide an insight to the impact of different communication technologies on the frequency regulation in power systems, particularly future smart grids with many loads to deliver a deterministic and necessary response to the grid. Note that using a 5G network can reduce the delay to 1-10 ms and help guarantee inertial response. The packet loss as an infinite delay can also be reduced using 5G network, and it can help provide a more reliable and secure grid.

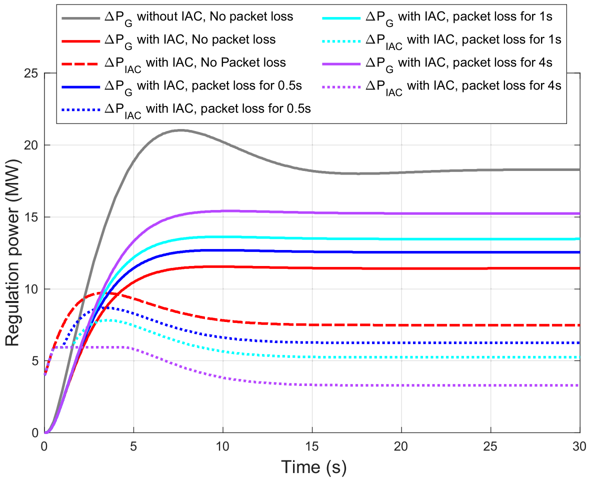

Fig. 8. The comparison of regulation power for different time durations of packet loss

V. CONCLUSIONS

This paper investigates the effect of communication delays and packet losses on inertia emulation using a power system model considering services provided by IACs. The results show that time delays and packet losses in the transmission of the RoCoF signal to the DR aggregator through the communication network can cause instability and/or severe frequency excursions. Therefore, adopting a new communication technology, such as 5G, with low latency and packet loss will have a significant impact in improving future smart grids with guaranteed inertia emulation performance. The investigation of communication impairments and 5G communications for inertia emulation and primary frequency control of large-scale power systems will be considered in the future work.

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