A Novel Centralized Remote Power Smoothing Architecture Incorporating Local Smoothing Compensation

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Abstract—**The increasing integration of intermittent renewable energy sources and some variable loads introduces fast power variations. These variations can impact grid stability, emphasizing the need for effective power smoothing strategies to ensure reliable grid operation. This paper introduces a novel centralized remote power smoothing (CRS) framework, where smoothing facilities are located away from the sources of power variations. The CRS is proposed as a novel market ancillary service that can be fully integrated within the existing automatic generation control (AGC) of power system operators. Further, to account for the practical implementation of CRS, the impact of communication delays is considered, which is subsequently mitigated in part through the proposed hybrid centralized-local smoothing approach. The feasibility of both CRS and hybrid smoothing is evaluated in comparison to the conventional local smoothing. Several case studies are conducted on the New England IEEE 39-Bus System, using real high-resolution renewable power and load profiles with 2–second granularity. The proposed CRS achieves up to 84% of the local smoothing performance using only 64% of its smoothing facilities' capacities.**

Index Terms—**Power Smoothing, Remote Power Smoothing, Frequency Regulation**

I. Introduction

Increasing concerns about global warming and greenhouse gas emissions have accelerated the widespread deployment of renewable energy sources (RESs). However, the large-scale integration of RESs into existing power systems presents significant operational challenges due to their intermittent and variable nature [1]. In particular, rapid power variations occurring over seconds to minutes can lead to frequency and voltage deviations, especially in weak or remote grids [2]. Moreover, such variability often requires additional reserve capacity for automatic generation control (AGC) to maintain system frequency within acceptable limits which might be a challenge in systems with high RESs penetration [3].

To address these operational challenges, extensive research has been conducted on power smoothing technologies and control strategies aimed at enhancing grid stability and accommodating the variability of RES output power. Among these technologies, energy storage systems (ESSs)—including battery energy storage systems (BESS), supercapacitors, and flywheel energy storage systems (FESS)—have gained significant attention in recent years. For example, [4] proposes a Gaussian-based method to smooth RES output power using a BESS. BESS technology offers high energy density and nearly constant terminal voltage during discharge, making it compact and suitable for voltage stabilization applications. However, its relatively limited cycle life, high energy capital cost, and particularly high power-related capital cost may significantly limit its economic viability when deployed solely for renewable smoothing (RS) purposes [5]. Supercapacitors also demonstrate strong capability in mitigating rapid power variations. In [6], novel control schemes are introduced to enable supercapacitors to smooth wind turbine output power and enhance low-voltage ride-through performance. Nevertheless, supercapacitors exhibit a linearly decreasing voltage profile during discharge, which complicates power management in applications requiring a regulated or constant voltage [7]. FESS technology provides several advantages, including high power density, fast ramping capability, and high round-trip efficiency [8]. For instance, [9] presents a method in which high-frequency wind power components are extracted and supplied to a model predictive controller to optimize the FESS charging and discharging process for output smoothing. However, FESS is typically characterized by short discharge durations—ranging from seconds to a few minutes—which limits its suitability to fast fluctuations with relatively low energy requirements [10].

It is noted that previous works on renewable smoothing primarily assume that the ESSs are co-located with RESs, e.g., wind and PV power plants—an approach that offers benefits such as reducing transmission losses and enabling faster response times. In many cases, however, local smoothing can be impractical due to spatial constraints, economically unfeasible due to high installation and maintenance costs, and limited flexibility and scalability. As renewable generation grows, the capacity for local smoothing may become insufficient, reducing its adaptability. Given these limitations, and in pursuit of greater flexibility, the authors of this work have recently introduced a direct remote smoothing (DRS) approach [2], where a specified smoothing facility (SF) is dedicated to remotely smooth the output power of a single RES.

This paper extends the DRS approach into a scalable and more versatile ancillary service framework. Specifically, we introduce the centralized remote smoothing (CRS) ancillary service, in which multiple non-smooth profile sources (NSPSs)—including RESs and second-level variable loads—are jointly smoothed by multiple SFs under a unified control architecture. Unlike traditional one-to-one smoothing schemes, where each SF is dedicated to a single NSPS, the CRS framework coordinates geographically remote SFs of different technologies to mitigate the aggregate power variations of all participating NSPSs. This coordinated structure enables

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various market participants to contribute to the CRS ancillary service and operate as SFs, thereby reducing the need for new dedicated smoothing infrastructure. Further, CRS can be seamlessly integrated into the existing AGC systems of power system operators, enhancing grid stability and operational flexibility. However, implementing CRS in practice requires wide-area communication networks, making it susceptible to communication delays that may degrade performance relative to local smoothing solutions. To address this limitation, the paper also proposes a hybrid approach that incorporates local SFs with limited capacities into the CRS framework, thereby mitigating potential performance issues arising from communication delays.

II. Centralized Remote Power Smoothing

This section explains the proposed CRS architecture and the impact of possible communication delay on its performance. Additionally, it introduces a hybrid centralized/local smoothing approach, which incorporates local limited SFs with the CRS to mitigate the communication delay impacts.

A. Delay-Free Centralized Remote Smoothing

In the proposed CRS, there is no dedicated SF for each NSPS. However, the power produced or consumed by all participating NSPSs is sent through a central communication network to the control center, where the centralized smoothing controller (CSC) determines the setpoints for all participating SFs and sends these setpoints to each facility via the same communication network. Fig. 1 shows a portion of a power grid (controlled area), $Area_i$, and the corresponding AGC and CSC. The system in the figure has R RESs and L variable loads, totaling $N = R + L$ NSPSs. The real-time power measurements of all NSPS (i.e., R RESs and L loads) are sent to the CSC in the control center, which then determines the setpoints of Z SFs. The total non-smoothed power injected into the system, P_{NS}^t, is calculated as the summation of the power measurements of the R RESs, $\sum_{r=1}^{R} P_{RES,\,r}^t$, and the L loads, $\sum_{l=1}^{L} P_{Load,\,l}^t$, below:

$$P_{NS}^t = \sum_{r=1}^{R} P_{RES,\,r}^t + \sum_{l=1}^{L} P_{Load,\,l}^t,\ \forall\, t \in \mathbb{T}. \tag{1}$$

The total smoothing power, denoted by SP_{CRS}^t and representing the sum of the individual contributions of all SFs, is determined as the MA of the non-smoothed power. as follows:

$$SP_{CRS}^t = \frac{1}{\tau}\int_{t-\tau}^{t} P_{NS}^t dt\ ,\ \forall\, t \in \mathbb{T}, \tag{2}$$

where τ represents the smoothing time in seconds.The total SF setpoint, SP_{CRS}^t, is then distributed among different SFs based on their rated assigned power for smoothing. As such, the contribution of each SF z (i.e., $SP_{SF_z}^t$) in SP_{CRS}^t is calculated as a percentage of its rated assigned power, $P_{SF_z}^{rate}$, allocated for CRS, relative to the total rated power of all SFs, $\sum_{z=1}^{Z} P_{SF_z}^{rate}$ as follows:

$$SP_{SF_z}^t = \frac{P_{SF_z}^{rate}\ SP_{CRS}^t}{\sum_{z=1}^{Z} P_{SF_z}^{rate}} \quad \forall\ z \in Z \wedge t \in \mathbb{T} \tag{3}$$

It is worth noting that, unlike conventional local smoothing strategies, introducing CRS as an ancillary service does not require explicitly accounting for the energy limits of participating SFs in the CSC. This is because each SF is responsible for following the CSC setpoints; if an SF is unable to do so, it should indicate that it is unavailable for participation in CRS during the given assignment period. Consequently, the grid operator can assign smoothing tasks to other available smoothing facilities.

B. Centralized Remote Smoothing with Communication Delay

As CRS relies on a continuously active, large-scale communication network, it may be affected by communication delays that can hinder its performance. This section recalculates the CRS setpoint assignments for the SFs under a one-way communication delay of δ. To represent the worst-case scenario, we assume that communication with all NSPSs and SFs experiences the same delay δ that represents the maximum one-way communication delay. Accordingly, the total non-smoothed power received by the CSC at time t is given by:

$$P_{NS}^t = \sum_{r=1}^{R} P_{RES,\,r}^{t-\delta} + \sum_{l=1}^{L} P_{Load,\,l}^{t-\delta},\ \forall\, t \in \mathbb{T}. \tag{4}$$

Similarly, under the assumption that distributing the setpoints to all participating smoothing facilities incurs the same communication delay δ, the actual applied smoothing power contribution of each SF z at time t (i.e., $SP_{SF_z}^t$) is updated as follows:

$$SP_{SF_z}^t = \frac{P_{SF_z}^{rate}\ SP_{CRS}^{t-\delta}}{\sum_{z=1}^{Z} P_{SF_z}^{rate}} \quad \forall\ z \in Z \wedge t \in \mathbb{T} \tag{5}$$

By substituting $SP_{CRS}^{t-\delta}$ from (2), and subsequently P_{NS}^t from (4), the contribution of each SF z at time t under a one-way communication delay δ is obtained as follows:

$$\begin{aligned} SP_{SF_z}^t &= \frac{P_{SF_z}^{rate}\ \frac{1}{\tau}\int_{t-\delta-\tau}^{t-\delta} P_{NS}^{t-\delta} dt}{\sum_{z=1}^{Z} P_{SF_z}^{rate}} \\ &= \frac{P_{SF_z}^{rate}\ \frac{1}{\tau}\int_{t-\delta-\tau}^{t-\delta} \left(\sum_{r=1}^{R} P_{RES,\,r}^{t-2\delta} + \sum_{l=1}^{L} P_{Load,\,l}^{t-2\delta}\right) dt}{\sum_{z=1}^{Z} P_{SF_z}^{rate}} \\ &\qquad \forall\ z \in Z \wedge t \in \mathbb{T} \end{aligned} \tag{6}$$

As in (6), $SP_{SF_z}^t$ depends on power measurements delayed by 2δ, which can partially deteriorate the performance of the CRS. Therefore, the following subsection II-C proposes a hybrid smoothing architecture in which the CRS is integrated with limited local smoothing to compensate for the 2δ-delayed CSC.

C. Hybrid Centralized/Local Smoothing

The philosophy of the proposed hybrid smoothing approach is to mitigate the deterioration in CRS performance caused by communication delays by leveraging local SFs. Recall Fig. 1, in which the "off" switches of the local SFs associated with the R RESs and L variable loads are now turned "on." Consequently, the illustrated portion of the grid is equipped with Z remote SFs participating in the CRS and receiving their setpoints from the CSC located at the control center, in addition to $N = R+L$ local SFs associated with the N NSPSs. These N local SFs, however, receive their setpoints locally and have no connection to the CSC. In other words, the N local SFs do not participate in the CRS ancillary service.

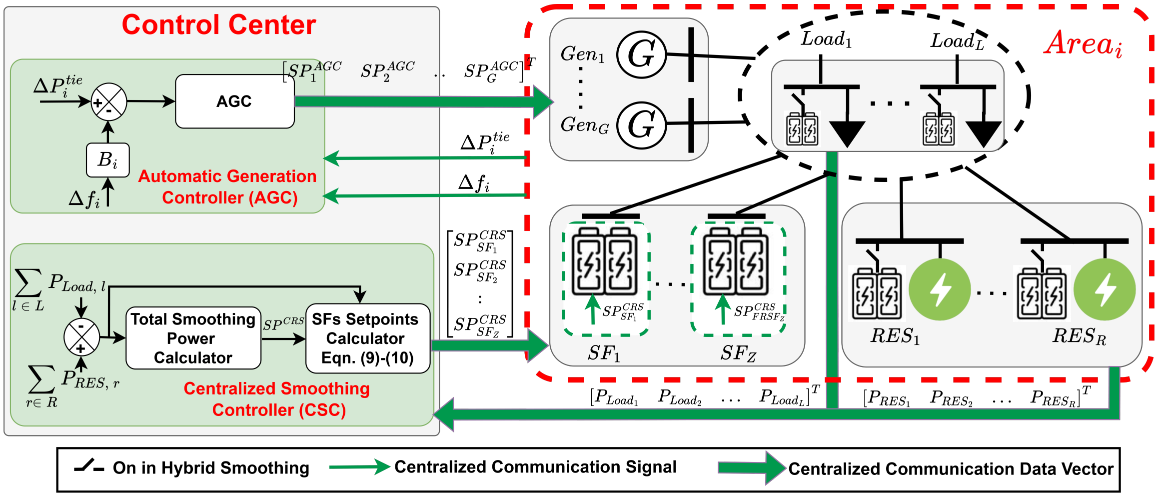

Fig. 1: Layout of the proposed centralized and hybrid smoothing architectures.

As explained earlier in (6), the setpoints received by the remote SFs at time t depend on the power measurements taken at time $t-2\delta$. Therefore, the local SFs are required to adjust the total power at the NSPS bus, n, at time t (i.e., $P^{t}_{bus,\ n}$) so that it matches the NSPS power at time $t-2\delta$ (i.e., $P^{t-2\delta}_{NSPS,\ n}$). In other words, the local SFs effectively delay the actual NSPS power profile by 2δ to align it with the delayed smoothing power injected by the Z remote SFs.

Consequently, the power setpoint of a local SF n, $SP^{t,local}_{SF_n}$, is calculated as the difference between the NSPS power at time $t-2\delta$ and t as follows:

$$SP^{t,local}_{SF_n} = P^{t-2\delta}_{NSPS,\ n} - P^{t}_{NSPS,\ n} \quad \forall\ n \in N \wedge t \in \mathbb{T} \tag{7}$$

Then the total power at the NSPS bus, n, at time t (i.e., $P^{t}_{bus,\ n}$) is matching the NSPS power at time $t-\delta$ as below:

$$P^{t}_{bus,\ n} = P^{t}_{NSPS,\ n} + SP^{t,local}_{SF_n} = P^{t-2\delta}_{NSPS,\ n} \quad \forall\ n \in N \wedge t \in \mathbb{T} \tag{8}$$

It is worth noting that if there is no communication delay, $\delta = 0$, then the setpoints of the local SFs will always be zero. Consequently, the local SFs are only required to restore the delay-free CRS performance when the system experiences a nonzero communication delay. Additionally, the local SFs' set points are capped at their rated power $SP^{rate,local}_{SF_n}$ limits, chosen based on the historical variation in the associated NSPSs' power profiles.

III. Centralized Smoothing as an Ancillary Service: Real-World Implementation

The provision of the CRS service as an ancillary service requires the definition of a clear operational and market procedure. The proposed framework is summarized as follows:

1) Market Participants: The CRS market consists of two categories of participants: Non-Smooth Power Sources (NSPSs), and Smoothing Facilities (SFs).

2) Measurement and Communication Requirements: i) Each NSPS shall transmit its real-time active power measurements at intervals not exceeding δ seconds; ii) Each SF shall be capable of receiving smoothing setpoints and updating its power output at intervals not exceeding δ seconds.

3) Assignment Period and Bidding Procedure: i) For each assignment period of $\mathcal{H}$ hours, the available SF participants,

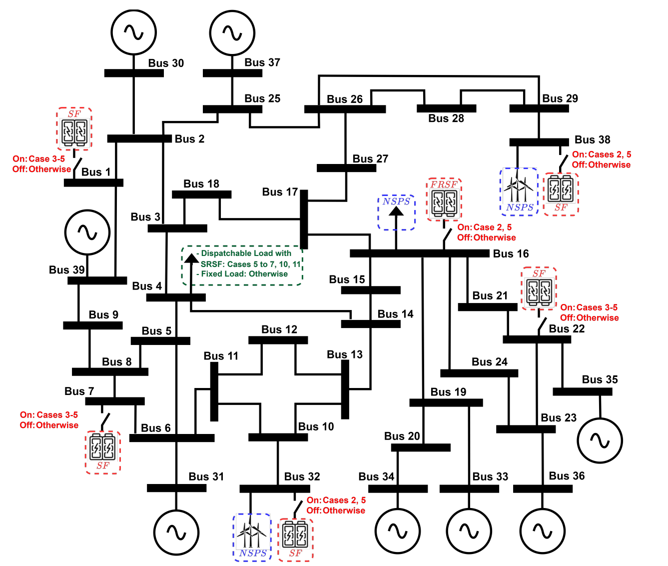

Fig. 2: Single line diagram of the modified IEEE 39-bus New England system.

denoted by the set $\mathcal{Q}$, shall be identified; ii) Each participating SF shall submit an offered price for providing power smoothing services in $/MWh.

4) Selection and Activation: i) The available SFs shall be ranked in ascending order of their offered participation prices; ii) The lowest-priced Z SFs shall be selected and activated to compensate for power variations and smooth the net injected power to the grid.

5) Operational Adequacy and Replacement Mechanism: i) The selected Z SFs shall have sufficient available power and energy capacity to cover the entire assignment period. ii) If any activated SF fails to meet its committed requirements, or if the smoothing demand exceeds the anticipated level, the system operator shall replace the deficient SF with another available SF from the remaining set $(\mathcal{Q}-Z)$ according to the merit order.

IV. Case Studies and Results

The introduced CRS and hybrid smoothing frameworks are validated through five case studies as summarized in Table I. The five case studies are conducted using the modified IEEE 39-bus New England benchmark system shown in Fig. 2.

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TABLE I: Summary of Case Studies

Cases	Case 1	Case 2	Case 3	Case 4	Case 5
Smoothing Approach	No Smoothing	Local Smoothing	Delay-Free CRS	Delayed CRS	Hybrid CRS/Local

TABLE II: Capacity of SFs and AGC Burden for Cases 1 to 5

Performance Metrics	Case 1	Case 2	Case 3	Case 4	Case 5
Local SFs (MW)	0	38	0	0	4.5
Local SFs (MWh)	0	5.6	0	0	1.2
CRS SFs (MW)	0	0	24	24	24
CRS SFs (MWh)	0	0	4.3	4.3	4.3
ΔC_{AGC} (MW)	14.6	10.3	11.3	12	11.3

The wind power and load power profiles are real, 2-second-resolution profiles obtained from wind plants and loads located in Ontario, Canada. In all cases, the smoothing time constant τ is set to 120 s. In Case 2, the local SFs are sized such that neither their power nor energy limits are reached at any time, thereby ensuring that the local smoothing operates under ideal conditions. All other modeling assumptions and operational settings for local smoothing (Case 2) follow the approach presented in [2].

A. Cases 1 to 3: Local Smoothing versus Delay-Free CRS

The performance of the local smoothing in Case 2 is compared with the base case (i.e., Case 1) and the proposed delay-free CRS. As shown in Fig. 3 (a), the system frequency in Case 2 with the local smoothing has much lower deviations and rate of change compared to the base case (Case 1) without any smoothing that relies only on the AGC for frequency regulation. Yet, when comparing Case 3 to Case 2, it is clear that the CRS, in its delay-free case, has slightly lower performance. A similar conclusion can be drawn from Fig. 3 (b), which shows that the total smoothed power in Case 3 is comparable to Case 2 but still has slightly more variability compared to Case 2. This slightly lower performance of the delay-free CRS compared to local smoothing is mainly due to the different grid losses resultant from injecting the smoothing power from SFs located away from the NSPSs.

Table II compares the needed SFs power and energy capacities and AGC burden of different case studies. As shown in the table, CRS in Case 3 reduces the AGC burden of Case 1 by 23%, compared to a 29% reduction achieved by local smoothing. This indicates that local smoothing provides a slightly greater reduction in AGC burden than CRS. However, in terms of smoothing facilities (SFs) capacity, the power capacity required for CRS is 24 MW, compared to 38 MW for local smoothing, representing a 36% reduction in required SF power capacity. Similarly, CRS requires 23% less SF energy capacity than local smoothing.

B. Cases 4 to 5: CRS with Communication Delay versus Hybrid Smoothing

In Cases 4 and 5, a one-way communication delay $\delta = 2sec$ is introduced to represent the worst-case scenario communication delay as defined by the regulations of the Independent Electricity System Operator (IESO) in Ontario [11]. In Case 4, the system frequency, as shown in Fig. 4 (a), shows an apparent performance deterioration compared to the delay-free CRS in Case 3. Nevertheless, when compared to Case 5 of the hybrid smoothing, Case 5 offers slightly better performance,

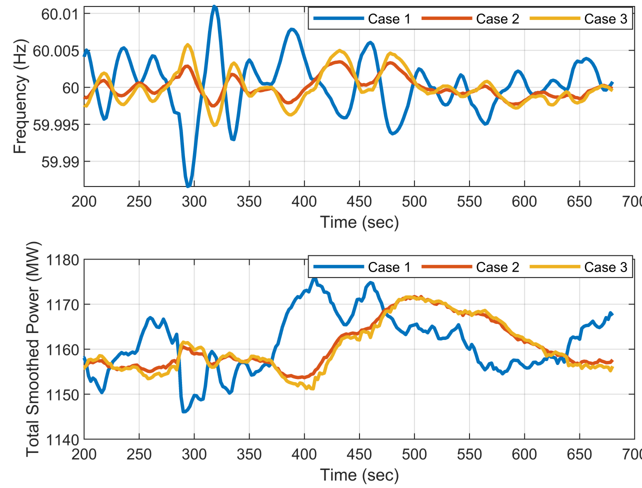

Fig. 3: (a) System frequency in Cases 1 to 3. (b) Total smoothed power in Cases 1 to 3.

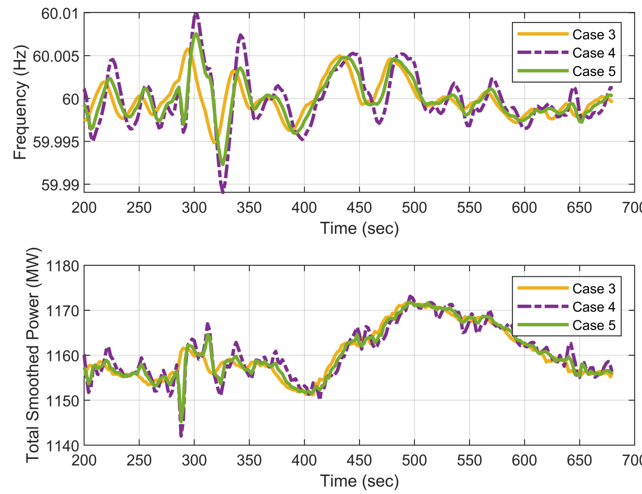

Fig. 4: (a) System frequency in Cases 3, 4 and 5. (b) Total smoothed power in Cases 3, 4 and 5.

with lower frequency deviation and rate of change. For instance, Case 5 has a 30% lower summation of the frequency absolute rate of change. Similarly, in Fig. 4 (b), the total smoothed power of Case 4 shows the deterioration impacts of the communication delay on the delay-free CRS performance and illustrates the partial mitigation achieved by the hybrid smoothing.

In terms of SF capacity, as shown in Table II, the hybrid smoothing approach requires 28.5 MW of combined remote and local SF capacity, compared to 24 MW for CRS and 38 MW for local smoothing. Therefore, hybrid smoothing still provides a 26% reduction in required SF capacity relative to conventional local smoothing. Regarding the AGC burden, Case 3 (delay-free CRS) achieves a reduction from 14.6 MW to 11.3 MW, corresponding to a 23% decrease. In contrast, Case 4 reduces the AGC burden from 14.6 MW to 12 MW, which represents a 17.8% reduction, indicating a performance degradation due to the delay effect. However, the hybrid smoothing approach in Case 5 restores the performance of Case 3, achieving the same 23% reduction in AGC burden as the delay-free CRS.

C. Implementation Challenges and Mitigation Strategies

The proposed CRS architecture reduces SFs' requirements, improves resource allocation flexibility, and leverages existing

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storage while avoiding costly new infrastructure. Its practical implementation, however, faces two main challenges: i) additional power losses from remote smoothing and ii) communication delays between NSPSs and smoothing facilities. Hybrid smoothing, as shown in Case 5, can partially mitigate these issues but may reduce some CRS benefits. This subsection highlights these challenges and outlines research directions to address them while preserving the advantages of CRS.

1) Power Losses Associated With Remote Smoothing: In centralized and hybrid configurations, smoothing power may be delivered through transmission networks from remotely located storage facilities. Unlike conventional local smoothing, this arrangement introduces additional network power losses due to line impedances and power flow redistribution. These losses may slightly reduce the effective smoothing accuracy and require higher injected smoothing power to compensate for the losses. Nevertheless, simulation results (e.g., Case 3) demonstrate that when communication delay is neglected, the centralized configuration achieves smoothing performance comparable to local smoothing while requiring 36% lower smoothing facility capacity. This indicates that the impact of power losses on overall smoothing performance is limited.

To further mitigate the impact of losses, the following strategies can be adopted: i) Optimal setpoint allocation (i.e., employ optimization algorithms to determine the optimal distribution of smoothing power among available SFs such that network losses are minimized while maintaining smoothing accuracy); ii) Loss-aware smoothing (i.e., incorporate estimated network losses into the smoothing control formulation); iii) Strategic SFs placement (i.e., Prioritize geographically or electrically closer storage resources to reduce transmission distances and associated losses).

2) Communication Delay: Centralized smoothing relies on real-time communication between NSPSs and SFs and the control center. Communication latency may degrade smoothing performance, particularly when the delay approaches or exceeds the smoothing update interval. As shown in Case 4, large communication delays can noticeably affect performance. It is important to note that the delay considered represents a worst-case scenario inspired by certain AGC implementations [11]. With modern high-speed communication technologies, significantly lower latencies can be achieved in practical systems.

Several mitigation strategies can be adopted to reduce the impact of communication delays: i) High-speed communication infrastructure using advanced communication networks to ensure low-latency data exchange; ii) Regulatory requirements by establishing technical standards that specify maximum allowable communication delays for participation in centralized smoothing services; and iii) Predictive techniques that implement short-term prediction algorithms for NSPS power profiles to compensate for expected delays and maintain effective smoothing performance.

V. Conclusion

This paper has presented a novel CRS framework designed to mitigate power variations arising from the increasing penetration of intermittent renewable resources and second-level load variations. Unlike conventional local smoothing approaches, the proposed CRS enables geographically remote facilities to provide smoothing support and can be seamlessly integrated into existing AGC structures as a new ancillary service. Through comprehensive case studies on the IEEE 39-Bus System using real 2-second resolution renewable and load data, the CRS demonstrated strong effectiveness, achieving up to 84% of the performance of local smoothing while requiring only 64% of the total smoothing capacity. However, possible communication delays in the practical implementation of CRS may partially degrade its performance, which has been mitigated by proposing a hybrid centralized/local smoothing approach. These results confirm the technical feasibility and advantages of CRS, highlighting its potential as a scalable and economically attractive solution for future grids. Future work will investigate the sensitivity of CRS performance to communication delays, NSPS power profiles, and electrical distance between NSPSs and SFs, and will develop detailed emergency management strategies for operation under limited SF availability.

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