Power Sharing-Based Framework for Allocating Automatic Generation Control in Distributed Energy Resources

Preprint

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Power Sharing-Based Framework for Allocating Automatic Generation Control in Distributed Energy Resources

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***Abstract*—The recent proliferation of distributed energy resources (DERs) in the power network along with the retirement of conventional generators has made it challenging to regulate system frequency. This paper presents a centralized control framework to leverage the potential of DERs in the distribution network to provide secondary frequency control services to the grid. The proposed framework is based on network volt-watt sensitivity analysis and takes into account DER operational and network-imposed constraints to allocate the automatic generation control (AGC) request among the aggregated units. The proposed framework was implemented on the IEEE 8,500-node test feeder and the results were validated against a standard linear programming-based scheme. Numerical results indicate that the proposed framework can successfully utilize the available power production headroom of the network to meet the AGC request while maintaining nodal voltages within acceptable limits.**

***Index Terms*—Distributed energy resources, distribution systems, secondary frequency control, virtual power plant**

I. INTRODUCTION

With the growing interest in energy decarbonization, DERs are expected to participate in grid frequency regulation services [1]. Currently, these services are provided by synchronous generators. On the one hand, large integration of renewables has introduced variability and uncertainty in the network owing to their stochastic nature. On the other hand, the displacement of conventional generators by DERs has rendered the power system in a state of reduced rotational inertia. Consequently, the existing paradigm of frequency regulation is being challenged.

DERs connected in the distribution network present the opportunity to utilize them for frequency response services. However, using these small-scale and intermittent resources for frequency regulation poses several challenges [2]. First, DERs are geographically dispersed in a network, and individual DER units might not have sufficient capacity or controllability required for grid support services. Second, unregulated variations in the power output of DERs can cause voltage limit violations in the distribution network. Third, quantifying the available power production headroom of DERs and modeling network constraints is challenging.

To address these challenges, the focus of this work is to coordinate DERs in the distribution network for reliable secondary frequency control (SFC) services. We propose a real-time AGC allocation framework to disaggregate the aggregated AGC signal among individual DERs in a computationally efficient manner while respecting the nodal voltage limitations. The proposed algorithm is hierarchical in nature and is based on network voltage sensitivity matrix (VSM) and linearized power flow equations. In the first stage, the operational constraints imposed by the DER and the network are computed. In the second stage, power output set-points are derived for participating DERs based on their available power generation capacity.

The main contributions of this work are as follows:

1) A real-time AGC allocation framework is developed that incorporates operational and network-imposed constraints of DERs. The proposed scheme can disaggregate AGC requests among individual DERs while maintaining nodal voltages within acceptable limits.
2) This work highlights the advantages of a power-sharing approach for AGC allocation in promoting the participation of DERs and in reducing linearization errors.
3) Different test metrics are presented to analyze the efficacy and performance of AGC allocation frameworks. These metrics can be used to compare different AGC allocation frameworks and optimize a given framework's performance.

A. Relevant Literature Review

Various approaches have been proposed for controlling aggregate DERs for frequency regulation services. The authors in [3] presented control frameworks for utilizing residential heating, ventilation, and air conditioning for SFC services. Authors in [4] presented fuzzy logic based controllers for provisioning SFC services using battery energy storage systems. These approaches, however, do not consider network constraints such as nodal voltage limits. The proposed framework, on the other hand, takes into account the effects of variations in power injection on nodal voltage profile.

The work of [5] considers a transmission and distribution co-simulation framework to investigate the provision of SFC services using DERs in the distribution network. A linear programming (LP) based model was formulated to disaggregate the AGC signal among DERs. [6] proposed an extremum-seeking-based control framework for utilizing DERs for transmission-level ancillary services.

In practice, the number of DERs in a network can be very large and solving optimization problems can be time-consuming. In addition to that, as the population of DERs in a network increases, communication latency problems can also arise, and any delay in the delivery of the AGC signal can cause stability problems [5]. Compared to the optimization-based approaches, the proposed approach requires much simpler computations and can be solved in a very fast manner.

The remainder of this paper is organized as follows. Section II discusses the preliminaries. Section III presents the proposed AGC allocation framework. The benchmark method and test metrics are presented in Section IV. Section V outlines the case study and numerical results. Finally, the conclusion is presented in Section VI.

II. PRELIMINARIES

A. DER Aggregation

The DER aggregation framework is enabled by two-way communication to utilize the power production headroom of DERs for frequency regulation. Power production headroom is the available extra power that DERs can dispatch for grid support services. A virtual power plant (VPP) is formed by aggregating the available DERs at the feeder head. The VPP is managed by a centralized aggregator. DERs participating in SFC services communicate with the aggregator to submit their available power production headroom, P_h. The DER aggregator coordinates with the transmission control center (TSC) to register its available power reserve, P_{vpp}.

Following frequency variation, SFC services are employed. Based on the reported headroom, the TSC issues a power injection/curtailment request, P_{agc}, to the aggregators. The aggregators utilize the proposed AGC allocation framework to disaggregate the requested power among the participating DERs while taking into account the physical constraints of individual units and the network voltage limitations set by the utility The DER aggregation model is schematized in Fig. 1.

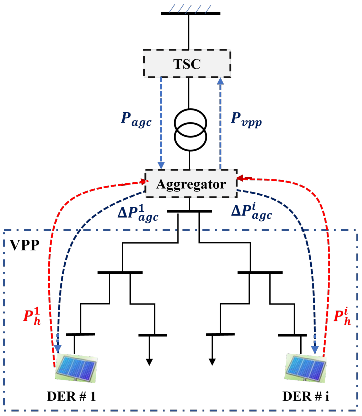

Fig. 1. Illustrative diagram of the DER aggregation scheme. DERs in the distribution network are aggregated into a VPP. Blue and red dashed lines represent the communication flow between an aggregator and individual units.

B. Voltage Sensitivity Matrix (VSM)

In a distribution network, the transmission line R/X ratio is high. This means that the dependence of nodal voltage on active power injections can not be neglected. Uncoordinated operation of DERs can cause voltage at certain nodes to violate the utility-set limits. The relationship between nodal voltage and active power injection is given by the following power flow equation:

$$P_i = \sum_{j=1}^{N_B} V_i V_j Y_{ij} cos(\theta_i - \theta_j - \phi_{ij})] \tag{1}$$

where P_i is the active power injection at node i, V_i and V_j are the voltages at nodes i and j, respectively, θ_i and θ_j are the voltage angles at nodes i and j, respectively, Y_{ij} and ϕ_{ij} are the magnitude and angle of the admittance of the branch connecting nodes i and j, respectively, and N_B is the total number of nodes.

(1) represents a non-linear relationship between V and P, which can make the analysis of network voltage response to DER power variations computationally intensive. However, for small perturbations around an operating point, network voltage can be approximated linearly using a first-order Taylor polynomial. Using Taylor's theorem;

$$\bar{V}(\bar{P}_0 + \Delta\bar{P}) \approx \bar{V}(\bar{P}_0) + \mathbf{M} \cdot (\Delta\bar{P}) \tag{2}$$

where $\bar{P}_0$, $\bar{V}(\bar{P}_0)$ are the vectors of DER power injections and network nodal voltages at some initial operating point, respectively, $\Delta\bar{P}$ is the power injection perturbation vector, $\bar{V}(\bar{P}_0 + \Delta\bar{P})$ is the network voltage post perturbation, and $\mathbf{M} = \nabla\bar{V}(\bar{P}_0)$ is the matrix of first order partial derivatives of $\bar{V}$ with respect to $\bar{P}$, and is referred to as the VSM. The VSM encapsulates the network volt-watt sensitivity.

This work uses the perturb-and-observe method [7] to construct the VSM. The idea is to observe the variations of network voltage in response to small perturbations in DER power injection by solving the power flow equations. The change in voltage at node n with respect to the change in power injection of DER m is computed as:

$$\frac{\Delta V_n}{\Delta P_m} = \frac{V_n^p - V_n^0}{P_m^p - P_n^0} \tag{3}$$

where V_n^0 and V_n^p are the voltage at node n before and after power perturbation, respectively, and P_m^0 and P_m^p are the power output of the m^{th} DER unit before and after power perturbation. This process is repeated in an iterative manner, for a single DER unit at a time, until exhausting all the available units. Using these measurements, the VSM is constructed as:

$$\mathbf{M} = \begin{bmatrix} \frac{\Delta V_1}{\Delta P_1} & \cdots & \frac{\Delta V_1}{\Delta P_m} \\ \vdots & \ddots & \vdots \\ \frac{\Delta V_n}{\Delta P_1} & \cdots & \frac{\Delta V_n}{\Delta P_m} \end{bmatrix} \tag{4}$$

III. PROPOSED METHODOLOGY

This section describes the proposed AGC allocation framework. The proposed algorithm has two stages: in the first stage, the power production headroom of the VPP is quantified; in the second stage, AGC share of individual DERs is derived.

A. Stage 1: Quantification of VPP Effective Headroom

The objective of this stage is to quantify the power production headroom of the VPP by taking into account network voltage limitations and the available power production capacity of the DERs. First, nodal voltage constraints are considered and the maximum amount of (active) power that can be injected at each DER node without causing any network-wide voltage violations is computed. Let $\bar{V}_{max}$ be a $N_B \times 1$ vector with the i^{th} element being equal to maximum voltage limit of the i^{th} node and let $\bar{V}(\bar{P}_0 + \Delta\bar{P}) = \bar{V}_{max}$. Using (2), the maximum injectable power at each node is computed as:

$$\Delta\bar{P}_{max} = \mathbf{M}^{-1} \times \left(\bar{V}_{max} - \bar{V}(\bar{P}_0)\right) \tag{5}$$

where $\mathbf{M}^{-1}$ is the inverse of the VSM and $\Delta\bar{P}_{max}$ is a vector whose elements, ΔP^i_{max}, correspond to the maximum real power that can be injected at each DER node such that network voltage limits are respected.

Next, the operational limits of DERs are incorporated by computing the effective headroom, P_{eff}, of each DER unit as:

$$P^i_{eff} = min(P^i_{max}, P^i_h) \tag{6}$$

where P^i_{eff} and P^i_h are the effective and the (physical) power production headroom of the i^{th} DER, respectively. Finally, the cumulative headroom of the VPP, P_{vpp}, is calculated as:

$$P_{vpp} = \sum_{i=1}^{M} P^i_{eff} \tag{7}$$

Note that P_{vpp} is constrained by the operational and network-imposed limitations on power injection at each DER node. The aggregator then registers the P_{vpp} to the TSC.

B. Stage 2: AGC Allocation

The objective here is to disaggregate the aggregated AGC signal among the individual DERs based on the effective headroom, P_{eff}, of each unit. The proposed power-sharing approach considers all the DERs in the VPP for the AGC services, and the share of each DER depends solely on network and operational conditions.

The inclusive approach to AGC allocation serves three purposes. First, by including the maximum number of available resources, it minimizes the AGC share of individual units and consequently, the linearization error associated with (2) is minimized. Second, it improves the reliability of ancillary services. Given the intermittent nature of DERs, by operating them below the maximum capacity, sudden changes in power generation of a subset of DER units will not have a significant impact on the total power output of the network. Third, it can promote the adoption of DERs by households

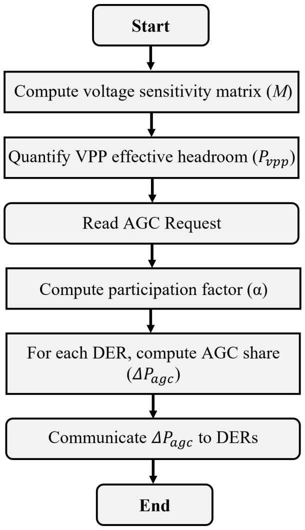

Fig. 2. Flowchart of the proposed AGC allocation framework.

Based on the AGC request from the TSC, P_{agc}, the aggregator computes the DER participation factor, α, as follows:

$$\alpha = \frac{P_{agc}}{P_{vpp}} \tag{8}$$

Using (8), the AGC share of each DER is computed as:

$$\Delta P_i = \alpha \times P^i_{eff} \tag{9}$$

where ΔP_i represents the AGC share of i^{th} DER unit. These new power references are communicated to the participating units, which can ultimately adjust their power output to meet the AGC request. A flow chart of the proposed AGC allocation framework is shown in Fig. 2.

IV. BENCHMARKING & TEST METRICS

A. Linear Programming (LP) based Method

A LP-based AGC allocation scheme is formulated for comparative analysis. The objective (10) is to derive optimal power output set-points for DERs in the VPP to meet the AGC request while minimizing nodal voltage fluctuations. The optimization problem is given as:

$$\min \quad |\mathbf{M} \times \Delta\bar{P}| \tag{10}$$

$$\text{s.t.} \quad V_{min} \le V_i + \Delta V_i \le V_{max} \quad \forall i = 1, \ldots, N_B \tag{11}$$

$$P_j + \Delta P_j \le P^{max}_j \quad \forall j = 1, \ldots, M \tag{12}$$

$$\sum_{j=1}^{M} \Delta P_j = P_{agc} \tag{13}$$

Constraint (11) ensures that the variation in nodal voltage due to power injection by the DERs remains within the defined limits. (12) deals with the operational constraints of DERs while (13) ensures that the total power dispatched by the DERs is equal to the requested power.

B. Test Metrics

The proposed method is validated against the LP-based method (10) using the following test metrics:

1) Response Ratio (R_{ratio}): The response ratio quantifies how closely the aggregator has fulfilled the AGC request. It is defined as:

$$R_{ratio} = \frac{P_{init} - P_{final}}{P_{agc}} \tag{14}$$

where P_{init} and P_{final} represent the power import of the network before and after SFC services, respectively.

2) Voltage Measurement Accuracy: Nodal voltages computed using (2) have an inherent linearization error. This error can be computed by solving the actual power flow. Error in voltage computations is quantified using the following metrics:

$$\bar{E}\ [\%] = \frac{|\bar{V}_{act} - \bar{V}_{comp}|}{\bar{V}_{act}} \times 100 \tag{15}$$

$$E_{avg}\ [\%] = \frac{1}{N}\sum_{k=1}^{N} E_k \tag{16}$$

where $\bar{V}_{act}$ and $\bar{V}_{comp}$ denote the vector of nodal voltages from the power flow solution and (2), respectively.

3) Computation Time: It refers to the time taken by a method to solve the AGC allocation problem.

V. CASE STUDIES AND RESULTS

The problem of AGC allocation in a large unbalanced distribution network is considered. The IEEE 8,500-node test feeder is modeled in OpenDSS. Case studies are performed on Intel i9-11900K with 32 GB DDR4 RAM. DERs are modeled as negative loads with a unity power factor. Each DER unit has an initial power output, P_0, of 1 kW and a power production headroom, P_h of 3 kW. Two different studies are conducted:

- Study 1: AGC request is kept constant at 200 kW while the number of DERs is varied.
- Study 2: The number of participating DERs remains constant at 200 while the AGC request is varied.

Fig. 3 compares the distribution of AGC share among the DER units for studies 1 & 2. Since the proposed methodology utilizes the maximum number of available resources, increasing the number of DERs resulted in a decrease in the AGC share of individual units. The LP-based method, on the other hand, utilizes a small subset of resources by pushing their output power to their maximum available capacity.

The effect of different philosophies of DER utilization on the accuracy of nodal voltage computation is depicted in Fig. 4. In general, both methods have a significantly small (percentage) error that decreases as the number of DERs increases. However, the LP-based method has greater variability and spread of approximation error than the proposed method.

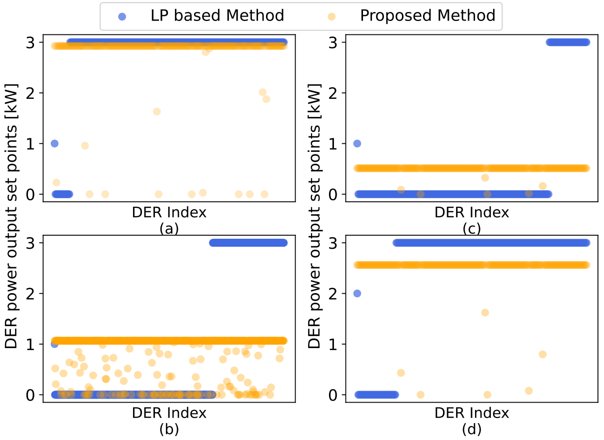

Fig. 3. Distribution of AGC share among DER units for study 1 and study 2. Study 1: The number of DERs varies from 150 (a) to 650 (b). Study 2: The AGC request varies from 100 kW (c) to 500 kW (d).

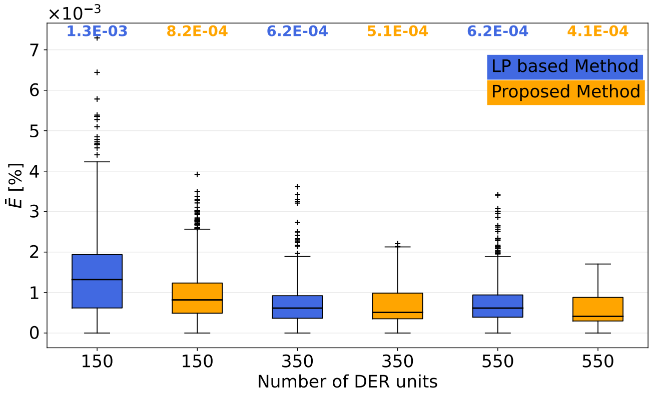

Fig. 4. Nodal voltage error statistics ($\bar{E}$ [%]) for study 1. E_{avg} [%] values are printed at the top of each box.

Figure Fig. 5 shows the box-plot graph of the error statistics in voltage computation using power set-points obtained using both methods for study 2. As the AGC request increases, the power set-points of participating units increase, which leads to an increase in the linearization error. These results indicate that using the LP-based method increases the vulnerability of nodal voltages to violate the set limits. The proposed AGC allocation framework, on the other hand, has a minimal approximation error and can effectively disaggregate the AGC signal while concurrently enforcing voltage limits.

Tables I and II present the response ratio of both methods for studies 1 and 2, respectively. As observed, both methods exhibit similar response ratios. Fig. 6 compares the computation time taken by both methods in solving the AGC allocation problem for studies 1 and 2. These results illustrate that the proposed method is significantly faster than the standard LP-based method.

These observations highlight the superiority of the proposed framework, indicating its scalability for the AGC allocation problem for large-scale networks in real-time.

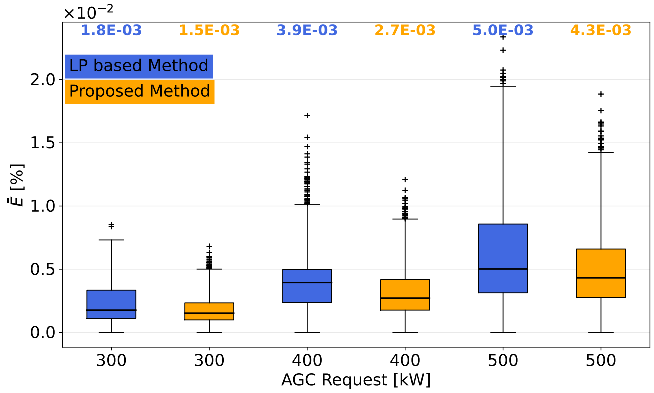

Fig. 5. Nodal voltage error statistics ($\bar{E}$ [%]) for study 2. E_{avg} [%] values are printed at the top of each box.

TABLE I
RESPONSE RATIO FOR STUDY 1

Number of DERs	Proposed Method	LP based Method
150	0.82	0.82
350	0.83	0.86
550	0.83	0.84

VI. CONCLUSION

This work proposed a centralized control framework to realize a coordinated response of DERs for SFC services. The framework considers DER operational and network-imposed constraints. Simulations are carried out under different test scenarios to corroborate the efficacy of the proposed framework in dispatching the aggregated AGC signal to individual DERs while enforcing voltage limitations. Through numerical simulations, it is demonstrated that:

- The proposed framework guarantees AGC delivery in a computationally efficient way while concurrently respecting the nodal voltage limitations.
- The proposed framework is on average three times faster than the standard LP-based method.
- Both methods achieved a similar response ratio of around 83%
- Compared to (10), the power output set-points obtained using the proposed method yield lower errors in nodal voltage computations.

Future work can incorporate distribution system internal losses and DER energy pricing in the AGC allocation framework.

TABLE II
RESPONSE RATIO FOR STUDY 2

AGC Request (kW)	Proposed Method	LP based Method
300	0.83	0.84
400	0.83	0.83
500	0.83	0.83

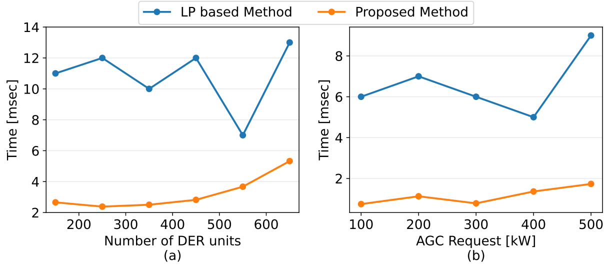

Fig. 6. Computation time for studies 1 & 2. (a) Study 1, (b) Study 2

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REFERENCES

[1] G. Strbac, D. Papadaskalopoulos, N. Chrysanthopoulos, *et al.*, “Decarbonization of Electricity Systems in Europe: Market Design Challenges,” *IEEE Power and Energy Magazine*, vol. 19, no. 1, pp. 53–63, Jan. 2021.

[2] M. Obi, T. Slay, and R. Bass, “Distributed energy resource aggregation using customer-owned equipment: A review of literature and standards,” *Energy Reports*, vol. 6, pp. 2358–2369, Nov. 2020.

[3] X. Chen, Q. Hu, Q. Shi, X. Quan, Z. Wu, and F. Li, “Residential HVAC Aggregation Based on Risk-averse Multi-armed Bandit Learning for Secondary Frequency Regulation,” *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 6, pp. 1160–1167, 2020.

[4] K. Wang, Y. Qiao, L. Xie, J. Li, Z. Lu, and H. Yang, “A Fuzzy Hierarchical Strategy for Improving Frequency Regulation of Battery Energy Storage System,” *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 4, pp. 689–698, 2021.

[5] W. Wang, X. Fang, H. Cui, F. Li, Y. Liu, and T. J. Overbye, “Transmission-and-Distribution Dynamic Co-Simulation Framework for Distributed Energy Resource Frequency Response,” *IEEE Transactions on Smart Grid*, vol. 13, no. 1, pp. 482–495, Jan. 2022.

[6] D. B. Arnold, M. D. Sankur, M. Negrete-Pincetic, and D. S. Callaway, “Model-Free Optimal Coordination of Distributed Energy Resources for Provisioning Transmission-Level Services,” *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 817–828, Jan. 2018.

[7] K. Christakou, J.-Y. LeBoudec, M. Paolone, and D.-C. Tomozei, “Efficient Computation of Sensitivity Coefficients of Node Voltages and Line Currents in Unbalanced Radial Electrical Distribution Networks,” *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 741–750, Jun. 2013.