Cloud-Based Framework for Operation and Control of Distributed Energy Resources

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***Abstract*—Modern power systems experience a steady increase in penetration levels of Distributed Energy Resources (DERs), which are gradually replacing conventional centralized generators. While the geographically distributed nature of DERs can provide opportunities for improving system operation, adopting conventional dedicated communication and control frameworks is not feasible over a wide area for small-sized DERs. This paper presents a cloud-based framework for communication, control, and coordinated operation of DERs. The work presented here adds to existing methodology by accounting for variations in DER performance and communication behavior. This paper establishes the communication and control requirements that enable DERs to interface with aggregators in a scalable and practical manner. The cloud architecture is described in detail and its practical implementation is demonstrated using Amazon Web Services (AWS). A power dispatch algorithm is developed to account for potential challenges of the proposed framework. The dispatch algorithm accounts for potential latency, jitter, and packet loss in the cloud-based communication as well as power production cost. To test the proposed framework, a real-time simulation setup is implemented using AWS, RTDS/RSCAD, and a communication middleware to emulate practical networks. A modified version of the IEEE 123 node test feeder is simulated on RTDS/RSCAD to capture real-world dynamics. Results demonstrate the capability of the aggregated-DER framework to follow online power mismatch and handle disturbances.**

***Index Terms*—cloud computing, distributed energy resources, distribution systems, real-time operation, amazon web services**

I. Introduction

The increasing penetration of Distributed Energy Resources (DERs) introduces new challenges for power system operation and control, particularly given their geographic dispersion and heterogeneous inverter designs. Order 2222 from the Federal Energy Regulatory Commission (FERC) further enables DERs and DER aggregations to participate in wholesale energy markets [1], which highlight the need for scalable coordination solutions. Cloud-based frameworks are a potential alternative for infrastructure needs, however, new vulnerabilities are introduced as a result of employing the cloud. Moreover, there are various inverter manufacturers with different specifications which results in different response times among DERs. Hence, it is not sufficient for a DER power dispatch algorithm to consider only production cost, but resulting DER response errors from communication vulnerabilities and varying response times need to be considered. Therefore, a framework is required for DER-aggregators to compensate the required infrastructure and account for the communication vulnerabilities and inverter disparities in dispatching power to DERs.

The large number of DERs integrated in the grid provides both benefits and challenges to the grid. The benefits include increased system reliability, flexibility, and security. However, the challenge is how to control this large number of decentralized resources. The dominant challenge is communication between DERs and operators. Operators can be distribution system operators (DSOs) or DER aggregators. Having a dedicated network for these resources is not feasible for large decentralized DERs [2]. Moreover, determining the flexibility of available DERs further intensifies these challenges. Existing work addresses this challenge by aggregating DERs into clusters in a hierarchical framework for secondary frequency control [3]. Also, the flexibility of DERs has been aggregated and modeled as virtual power plants [4]. Furthermore, cloud-based approaches arise to mitigate the challenge of decentralized resources. In [5], DER participation in frequency regulation has been facilitated by utilizing wired and wireless communication to reduce uncertainty in DER controllability. The authors in [6] present a cloud-hosted control scheme to improve planning of power systems, achieving enhanced reliability and stability. Moreover, a digital twin architecture has been integrated on the cloud to support coordination of DERs and efficient decision-making. In [7], a cloud-based control has been utilized to optimize the aggregation of dispersed resources.

The communication architecture is a crucial component for effective cloud-based control. The authors in [8], have presented a cloud-assisted microgrid that elevates efficient energy sharing. Additionally, their work evaluates using Message Queuing Telemetry Transport (MQTT) and the interactions of the functions on the cloud. In addition, the authors illustrate enhanced control of decentralized resources with minimal latency and high scalability. The authors in [9] present a conceptual model incorporating the use of AWS Lambda for power system regulation. Meanwhile, the use of a real-time digital simulator (RTDS) for testing new approaches is crucial to ensure the reliability and practicality of the proposed approaches. In a prior work [10], [11], the performance of a cloud-based multilevel control infrastructure for secondary frequency control is assessed using RTDS prior to implementation on NV Energy's distribution feeders.

Despite ongoing efforts, accurately evaluating the performance of DERs remains a significant challenge. Performance

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of DERs is dependent upon two major factors, flexibility and controllability of DERs. Many existing approaches depend on probabilistic techniques to predict DER output, particularly for renewable energy resources. However, such methods fail to capture real-time conditions, thus produces errors in determining DERs flexibility. Also, aggregation-based studies assume accurate communications and reliable DERs. Hence, it is required to have a model that captures real-world behaviors of variable DERs and communication vulnerabilities.

This paper presents a cloud-based framework to meet the control and communication requirements of DER-aggregators. The computational power required for control and communication protocol and infrastructure are realized through cloud resources. A detailed example is presented using Amazon Web Services (AWS), with the specific resources required to realize the proposed framework. The same concept can also be implemented on other commercial cloud platforms or on a private cloud. A power dispatch algorithm is developed with considerations for DER performance reliability to ensure an economic and appropriate response to mismatches and disturbances. Resulting dispatch challenges from cloud-communication vulnerabilities and varying inverter response are handled by introducing communication and operation health indices. The validity of the proposed approach is tested through a modified IEEE 123 node test feeder on a Real-Time Digital Simulator (RTDS) to capture realistic system dynamics. The system includes 59 DERs being actively coordinated by the cloud-hosted control logic. A communication middleware is also utilized between the RTDS simulated system and AWS to model potential communication failures. Real-time simulation results are presented and demonstrate the ability of the proposed framework to handle power disturbances.

Rest of the paper is organized as follows. Section II discusses the developed power dispatch algorithm for DERs. Section III presents the DER control framework. The case study and results are presented in Section IV. Finally, conclusions and future considerations are discussed in Section V.

II. Proposed Dispatch Algorithm for DERs

This section details the methodology for cloud-based control that determines the optimal, reliable, and cost-effective dispatch of DERs to handle real-time power mismatch in power systems. The core principle is to minimize operational costs while ensuring system stability and adhering to DER operational limits. The cloud-hosted logic dynamically allocates power setpoints to available DERs based on real-time power variations. The proposed framework utilizes a cost-conscious linear allocation model for setpoint calculations during power discrepancies. The total increase in the demand for the system above the available power is defined as ΔP. The cloud-hosted logic distributes an existing power imbalance to N DERs using a weighted proportional approach. Total power mismatch is calculated as follows.

$$\Delta P = P_{\text{demand}} - P_{\text{sub}} \tag{1}$$

where P_{demand} is the active power demand at the substation, and P_{sub} is the available active power at the substation.

Power balance equality constraints are then expressed for total power mismatch and DERs as follows.

$$\Delta P = \sum_{i=1}^{N} \Delta P_{\text{DER i}} \tag{2}$$

$$P_{\text{DER i}}^{m+1} = P_{\text{DER i}}^{m} + \Delta P_{\text{DER i}}^{m} \tag{3}$$

where $\Delta P_{\text{DER i}}^{m}$ is the allocated change in active power output from DER i at the m^{th} time instant, $P_{\text{DER i}}^{m}$ is the current active power output of DER i, and $P_{\text{DER i}}^{m+1}$ is the new set points of active power of DER i at $m+1$. Operational constraints of DERs are formulated as follows.

$$P_{\text{DER i}}^{\min} \leq P_{\text{DER i}} \leq P_{\text{DER i}}^{\max} \tag{4}$$

where $P_{\text{DER i}}^{\min}$ is the minimum active power production of DER i and $P_{\text{DER i}}^{\max}$ is the maximum active power production of DER i. In the presented approach, while controlling multiple DERs, there might be some cases where DERs are sent commands to change their output by relatively small amounts. Whereas this solution is feasible, it is not practical to send such small changes for a large number of DERs which can lead to network congestion. Thus, a new constraint is added to the optimization framework to limit the minimum change of each DER output. It is assumed that the minimum change in DERs output is relative to its maximum output power by a factor α, which is presented by the following equation.

$$|\Delta P_i| \geq \alpha \cdot P_i^{max} \tag{5}$$

The set points are only sent to the DERs which have new set points. The total cost of power production (C_t) is calculated using (6).

$$C_t = \sum_{i=1}^{N} c_i P_{\text{DER i}} \tag{6}$$

where c_i is the power production cost of DER i. This work accounts for the reliability of the DERs by including a state coefficient (s_i) of each DER. The state coefficient is estimated by monitoring the connection of the DER and the response to previous commands. A gain (ψ) is implemented in the equation of the objective function to represent the cost of reliability for operators. The objective function is formulated as follows.

$$\min f = \sum_{i=1}^{N} (c_i + \psi s_i) P_{\text{DER i}} \tag{7}$$

Given a vector C of the cost of DERs, S is a vector of state coefficient of all DERs, and P_{DER} is a vector of the power output of all DERs, a vector form representation is obtained as follows.

$$\min f = (C + \psi S) \cdot P_{\text{DER i}}^{\top} \tag{8}$$

The cloud-hosted optimization logic requires an accurate, dynamic measure of each DER's availability and performance, encapsulated by the state coefficient s_i. A high s_i value,

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representing high risk or unreliability, increases the effective cost of the DER in the objective function, thus reducing its dispatch. The proposed state coefficient s_i is derived from a newly defined reliability index R_i, where the two are inversely related:

$$s_i = 1 - R_i \tag{9}$$

This method guarantees that reliable and lower-cost DERs receive higher priority with proportionally greater portions of power production.

An exponential weighting factor (λ_k) is applied to the historical data to prioritize recent performance, where $k = 0, 1, 2$. $k = 2$ represents the most recent time step (current control cycle minus one) and $k = 0$ represents the oldest (third most recent). The unnormalized weights are e^k for k=0,1,2. The normalized weight for the k-th time step, λ_k, is then obtained as follows.

$$\lambda_k = \frac{e^k}{\sum_{j=0}^{2} e^j} \tag{10}$$

The sum of the three normalized weights is equal to one. The connection state ($\epsilon_{i,k}$) reflects the fundamental availability of the DER i at time step k.

$$\epsilon_{i,k} = \begin{cases} 1, & \text{if DER } i \text{ was connected} \\ 0, & \text{if DER } i \text{ was disconnected} \end{cases} \tag{11}$$

The response accuracy coefficient ($a_{i,k}$) quantifies the DER i's compliance with the previous commanded active power change $\Delta P_{\text{cmd},k}$.

$$a_{i,k} = 1 - \left(\frac{\Delta P_{\text{actual},k} - \Delta P_{\text{cmd},k}}{\Delta P_{\text{cmd},k}} \right)^2 \tag{12}$$

where $\Delta P_{\text{cmd},k}$ is the active power change commanded by the control logic at time step k, and $\Delta P_{\text{actual},k}$ is the actual observed active power change of DER i at time step k. This formulation penalizes deviations from the commanded setpoint, where a perfect response ($\Delta P_{\text{actual},k} = \Delta P_{\text{cmd},k}$) yields $a_{i,k} = 1$, and significant deviations result in values closer to zero or negative. The final reliability index R_i is the average of the weighted historical connection states and weighted historical response accuracies

$$R_i = \frac{1}{2} \sum_{k=0}^{2} \lambda_k \left(\epsilon_{i,k} + a_{i,k} \right) \tag{13}$$

The state coefficient s_i is then updated using (9). This real-time, performance-based s_i value is then used in the objective function (7) to adjust the dispatch priority of DERi.

III. Cloud-Based Infrastructure and System Architecture

Power systems are mainly lagging behind with regards to the implementation of cloud-based technologies. This reluctance stems from regulations such as the North American Electric Reliability Corporation (NERC)-Critical Infrastructure Protection (CIP) standards [12]. However, DERs are usually much smaller than the required limit to be considered as a CIP and are excluded from such standards [13]. Cloud-based solutions can then be employed to provide adequate communication and control infrastructure for DERs, which is not otherwise feasible given their smaller sizes and distributed nature. Cloud providers such as AWS also offer cyber-security tools that can ensure the secure operation of DERs. This paper develops a framework for coordinating the operation and control of DERs through a cloud-based logic while discussing the required cloud services to emulate conventional power system contols and communications. The framework is implemented using the RTDS hardware, a middleware script, and an event-driven cloud architecture. The test system is modeled and integrated DERs in RSCAD (the graphical user interface of RTDS). RTDS executes real-time electromagnetic transient (EMT) simulations that represent inverter-based resources with high precision. A python script is embedded within RSCAD to simulate load changes of the system and flexibility of DERs. Data exchange between RTDS and the middleware script is facilitated by using GTNETx2 card. GTNETx2 card is a communication card which is connected to the RTDS by fiber optic cables and allows the RTDS to send and receive data through the communication network. The middleware script is used to simulate failures in the communication network. In this work, the GTNETx2 card is used to exchange floating-point values over TCP/IP, enabling continuous transmission of measurements and reception of updated control setpoints.

The Python middleware maintains a persistent socket connection with the RTDS and interfaces with AWS IoT Core through MQTT [14]. It packages RTDS measurements into JSON, publishes them to predefined MQTT topics, and parses incoming cloud responses before forwarding them back to the simulator. To emulate realistic communication behavior, the middleware also introduces delays, jitter, and packet losses. This layer effectively reconciles the deterministic timing of the RTDS with the asynchronous characteristics of cloud services. On the cloud side, AWS IoT Core manages message routing and enforces topic-based organization for different data streams. IoT Rules filter and forward MQTT messages to AWS Lambda, which performs event-driven processing and computes updated control actions. The use of JSON ensures consistent formatting of active and reactive power measurements across all components, enabling multiple DER streams or controllers to operate simultaneously without collision. This architecture remains modular and scalable, as the data source and the processing logic (Lambda) are fully decoupled.

Cloud computing offers advantages for real-time supervisory control because its services can scale elastically and operate independently of local hardware constraints. FaaS platforms such as AWS Lambda provide stateless, event-triggered execution suitable for lightweight control functions [15]. AWS IoT Core further supports secure, low-overhead MQTT communication, while isolated Lambda environments reduce resource contention and allow parallel execution. Together, these services enable rapid updates to control logic, built-in monitoring, and strong security practices. Although cloud latency (typically 100–500 ms for MQTT) remains unsuitable for primary protection, it is appropriate for secondary-level corrective actions [16]. As noted in recent studies, cloud-integrated architectures continue to expand in power system monitoring, coordination of DERs, and hybrid HIL experimentation [11], [17]. In this work, the focus is on analyzing the effects of communication failures rather than replicating their exact mechanisms. While specialized tools exist for detailed network emulation, the implemented middleware is sufficient to impose realistic delay and packet-loss patterns, providing an accurate approximation of network-induced disturbances and their impact on cloud-based DER coordination.

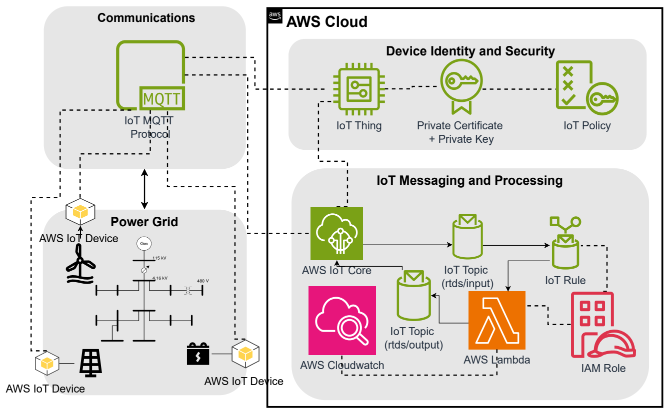

Fig. 1: Proposed Communication and Control Framework

IV. Case Study and Results

This case study evaluates the feasibility of cloud-based control for real-time distribution system operation, in which the cloud allocates active power setpoints to a large fleet of DERs. The output power measurements and flexibility of each DER are sent to the optimization engine on the cloud. Then the optimal new set points allocated by the optimization engine are sent to each DER. Furthermore, communication contingencies are simulated to represent real-world implementation challenges. The analysis is conducted on a modified version of the IEEE 123 node test feeder [18] to include 59 DER units that are arbitrarily distributed across system nodes. The DER power ratings follow a uniform distribution between 10 kW and 50 kW, yielding a total maximum available capacity of approximately 1770 kW. The loads of the test feeder vary over time, creating realistic disturbances that require cloud-based controller to rebalance the system dynamically. This framework can be utilized to allow aggregated DERs to participate in secondary frequency control, real-time cost minimization, and system load management. In this case study, the framework is used to maintain the overall system load below a certain threshold, which is 3.3 MW in this work. Thus, the available DERs are utilized to compensate for load changes and component failures.

The RTDS is utilized to run the test system, including DERs. A network communication card (GTNETx2) designed for RTDS is used to enable bidirectional data exchange between the simulated system in the RTDS and the cloud-based framework. Active power measurements are transmitted via TCP/IP to the cloud, while updated DER setpoints generated by the optimization engine on cloud are received and mapped to dedicated control variables in the simulation environment. A middleware script is used to simulate communication contingencies between RTDS and the cloud. Although the round-trip communication delay typically ranges between 200 ms and 300 ms, a one-second interval is integrated to mitigate message overlap and reduce network jitter. This interval remains sufficiently fast for many power system control and operational schemes, including frequency regulation, peak-load shaving, and volt-VAR control, all of which operate on slower time scales. At each control cycle, the measurement data are published to AWS IoT Core, converted to JSON format, and forwarded to an AWS Lambda function that executes the allocation algorithm. When the measured system load exceeds a predefined threshold, the optimization engine determines optimal DER power injections subject to individual physical limits. The resulting setpoints are then transmitted back to the RTDS. When no mismatch exists, the cloud returns zero-change commands to avoid unnecessary actuation. After each command, the framework is set to wait four seconds for the system to reach a steady-state point, based on system analysis done in field integration [11]. The MQTT communication channels are uniquely indexed to prevent collisions, and secure operation is ensured through certificate-based authentication, IAM role permissions, and restricted routing rules.

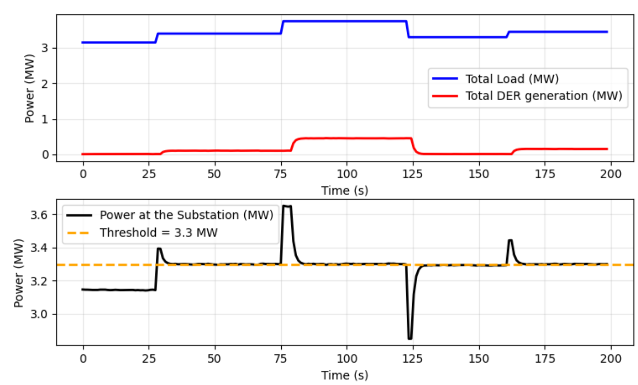

Fig. 2: DERs Output for Maintaining System Load Below Threshold

The performance of the framework to maintain the overall load of the grid below the threshold is shown in Fig. 2. The blue curve shows the total system load. The red curve shows the total output of all DERs. The objective is to maintain the black curve—representing the net system load at the substation—at or under the dashed line, which corresponds to the 3.3 MW threshold. As the cost of load consumption is less than power generated from DERs, the output of DERs is reduced when the load is below the threshold. This highlights the enhanced performance of the framework. Also, a risk index is integrated in the framework to increase the reliability of the model, which can be seen in Fig. 3. The curves show the total residual power of the system above the threshold. This error

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is caused by DER failures and communication contingencies. There is a significantly higher residual power when the risk index is not included in the framework. The comparison demonstrates that integrating the risk index substantially reduces residual errors, thereby improving robustness against communication and actuation uncertainties. Overall, the results demonstrate that the proposed cloud-based framework can reliably coordinate a large fleet of DERs in real time, even under communication delays, jitter, and losses, while maintaining system loading within prescribed limits. These findings highlight the potential of cloud-integrated coordination strategies to scale toward larger distribution networks and more complex multi-service operational objectives.

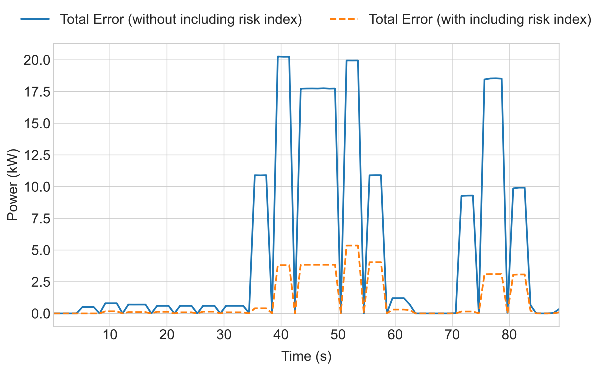

Fig. 3: Total Residual Power of the System Above Threshold

V. Conclusion

This work has demonstrated the enhanced operation and control of decentralized DERs. A cloud-based framework is developed, integrating optimization model to reduce energy cost while ensuring reliability of DERs. The model has incorporated risk index that tracks the state of each DER to determine its state of connection. Additionally, communication contingencies and DERs response have been estimated by identifying errors the performance of DERs. Furthermore, a case study has been conducted to validate the proposed approach. This study has utilized RTDS to simulate grid behaviors in real-time. DERs are modeled within the RTDS. The optimizer is implemented in AWS. The communication between DERs and AWS is modeled by integrating a middleware script that simulated communication contingencies. The obtained results has confirmed the applicability, scalability, and reliability of the proposed approach in operation and control of DERs. Moreover, Fig. 3 has illustrated the robustness of the framework in mitigating the errors influenced by communication and DERs failures.

In this work we are focused on the impact of network failures not the way it fails. Although there are dedicated software to simulate network behaviors, the utilized middleware is sufficient to perform the required simulation as it provides an accurate presentation of the impact of communication network contingencies. This framework can be utilized by aggregators and distribution system operators to reduce costs, allow DERs to participate in frequency regulations, and control demand responsive loads. Although the framework has mitigated the need of dedicated communication infrastructure to control the large number of decentralized DERs, cyber-security remains a concern with the increased surface of attacks, influenced by integrating DERs.

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