Study of Communication Boundaries of Primal-Dual Based Distributed Energy Resource Management Systems (DERMS)

Preprint

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National Renewable Energy Laboratory

Presented at the 2023 IEEE Conference on Innovative Smart Grid Technologies North America (ISGT NA)
Washington, D.C.
January 16–19, 2023

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-83995
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Suggested Citation
Comden, Joshua, Jing Wang, and Andrey Bernstein. 2023. *Study of Communication Boundaries of Primal-Dual Based Distributed Energy Resource Management Systems (DERMS): Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-83995. https://www.nrel.gov/docs/fy23osti/83995.pdf.

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Study of Communication Boundaries of Primal-Dual-Based Distributed Energy Resource Management Systems (DERMS)

Joshua Comden, Jing Wang, and Andrey Bernstein

***Abstract*— As the coordination of distributed energy resources becomes more necessary to provide grid services through a distributed energy resource management system (DERMS), studying the communication requirements for successful real-world, low-cost implementation becomes increasingly important. Specifically, this paper studies the necessary communication time resolutions between the different system components for a primal-dual-based DERMS, a highly developed DERMS framework. We design a metric to evaluate the functionality of a DERMS with respect to providing grid services. Using numerical simulations based on a real-world feeder in Colorado, we show that the upper bound on the time resolutions is on the order of minutes instead of the previously assumed order of seconds.**

I. Introduction

With the increasing number of distributed energy resources (DERs) being installed in distribution networks, their coordinated management will be important to maintain stability and even provide services to the wider grid. This has become even more imperative with the declaration of Federal Energy Regulatory Commission Order No. 2222, which opens wholesale markets for DER aggregator participation [1].

For this reason, the general framework of distributed energy resource management systems (DERMS) was envisioned. DERMS are control schemes that aggregate, integrate, and manage multiple DERs to provide grid services (e.g., voltage support). A unique grid service that can be provided by a DERMS is a virtual power plant (VPP), in which a group of DERs on a feeder is controlled as a block to keep the power imported into a distribution feeder at the feeder head within an interval around a time-varying set point. This turns the feeder into a semicontrollable resource for a distribution network operator by allowing the VPP set point to be adjusted for higher level grid objectives. A DERMS can be operated in coordination with other grid controls by a utility or a third-party aggregator [2].

One of the most developed classes of DERMS is based on primal-dual control [3], where a centralized coordinator collects measurements (e.g., voltage magnitudes, feeder head powers) of the distribution network and sends out control signals to distributed local controllers, each of which controls one or a couple of DERs [4]. This class has been customized to support different selections of grid services, including voltage regulation [5], [6], [7]; voltage regulation and VPPs [8], [9], [10], [11], [12], [13]; and voltage regulation, line current constraints, and VPPs [4].

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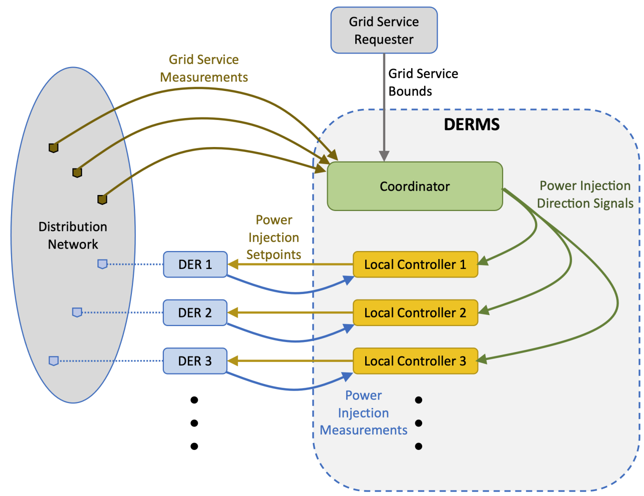


Fig. 1: Information flow of primal-dual-based DERMS

Operating a DERMS requires communication infrastructure to send various types of messages between the different control components. In the case of primal-dual-based DERMS, the operation requires measurements being sent to the DERMS coordinator from various parts of the distribution network, control signals sent to the distributed local controllers from the coordinator, and set points sent to the DERs from the local controllers. Further, current DERMS development and evaluation assumes that there is access to communication infrastructure that can support messages being sent between all of the control components every couple of seconds (e.g., [11]). Very little work has been done, however, to investigate the communication requirements in two critical aspects: (i) the time resolution specifications between each control component and (ii) the impact of communication issues on DERMS performance. The focus of this paper is on (i), whereas (ii) will be future work.

If this assumption on the time resolution can be significantly relaxed while keeping the DERMS functional, then the communication infrastructure cost will be much lower and allow for easier commercialization. Thus, the objective of this study is to find the upper bound on the communication time resolution between the different control components for a primal-dual-based DERMS. This paper makes the following contributions:

1) We describe in detail the communication architecture of primal-dual-based DERMS to highlight key differences between each type of communication channel. (Section II)

2) We design evaluation metrics based on grid service performance that determine when the DERMS is functional or not to provide the upper bound on the time resolution. (Section III)
3) We use numerical simulations of a real-world feeder and the system's communication channels to find the upper bound on the time resolution. (Section IV)

II. Communication Architecture

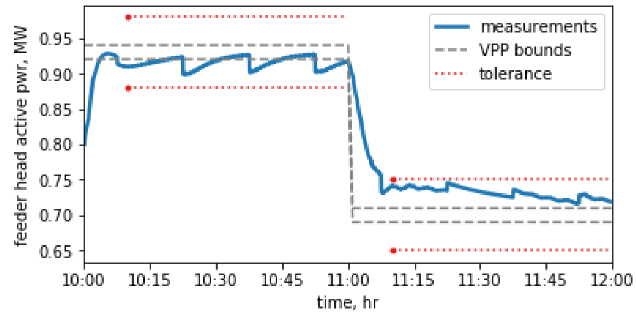
In this section, we describe the communication architecture and time resolution properties of primal-dual-based DERMS.

The DERMS works as a feedback controller [3] of a distribution network (see Fig. 1), where a grid service requester sets the reference grid service bounds, the grid service measurements (e.g., voltage measurements) are the feedback, and the power injections provided by the DERs are the control variables. Inside of the DERMS, the coordinator translates the grid service measurements that are outside of their associated bounds into individualized power injection direction signals. The distributed local controllers use the direction signals to adjust the power injection set points of their associated DERs [4]. From this general control structure, we classify the communication channels between the different control components into the following categories:

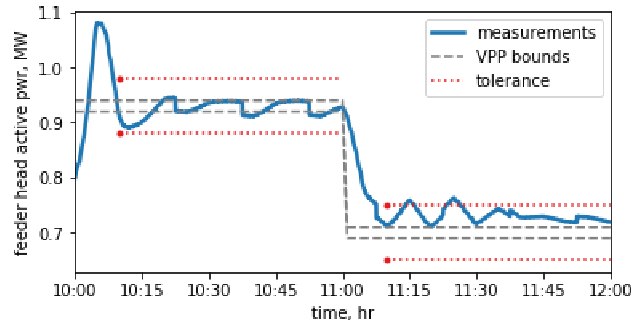
1) Grid service measurements to DERMS coordinator
2) DERMS coordinator to local controllers
3) Local controller and DER(s).

The first category requires infrastructure, such as a supervisory control and data acquisition (SCADA) system, to send the grid service measurements from various locations on a distribution network to the DERMS coordinator. The time resolution might be set differently depending on the spatial distribution of the grid service being provided. For instance, a VPP service needs only the power measurements from, at most, three locations to account for the three phases at the feeder head, whereas a voltage support service requires voltage magnitude measurements from hundreds or thousands of locations spread apart. Because the voltage support service already requires a more complex communication system, having a design specification for a small time resolution could make the infrastructure cost prohibitively expensive. On the other hand, because the VPP depends on, at most, three communicated measurements, the communication infrastructure needed to ensure its reliable operation might already allow for design specifications with a small time resolution.

The second communication channel category also requires infrastructure, such as a SCADA, to send individualized power injection direction signals from the DERMS coordinator to the hundreds of local controllers that are widely distributed across the distribution network. The time resolution for all of these channels could have the same time resolution because the coordinator will calculate the direction signals at the same time; however, it is possible for resolutions to be different if they are communicated over different third-party communication platforms, where the availability of the platform depends on the location of the local controller.



(a) Functioning VPP grid service



(b) Not functioning VPP grid service

Fig. 2: Example of a VPP grid service that is either (a) functioning or (b) not functioning based on a set tolerance outside of the VPP bounds after a disturbance.

The final category is the bidirectional communication between the local controller and its associated DER(s). Because the communication between these two components is simpler and the local controller is intended to be in close proximity to the DER(s) it controls, the time resolution has the potential to be much smaller than that of the other two communication channel categories. Each local controller might have a different communication time resolution with its associated DER(s), depending on whether it hardwired or using wireless communication.

The global impact of the time resolutions is that the maximum time resolution among all three categories limits the number of full control iterations or cycles that can be performed through the DERMS within a given amount of time; this can hinder the quality of the grid services provided.

III. Communication Evaluation Metrics

As we push the time resolution limits for the different communication channel categories, we need to define an evaluation metric that determines whether the DERMS is behaving in a functional manner or not.

Ideally, after a large disturbance, a DERMS can quickly bring the grid service measurements back to within their requested bounds. The quality of the DERMS can be graded by how quickly the grid service measurements can be

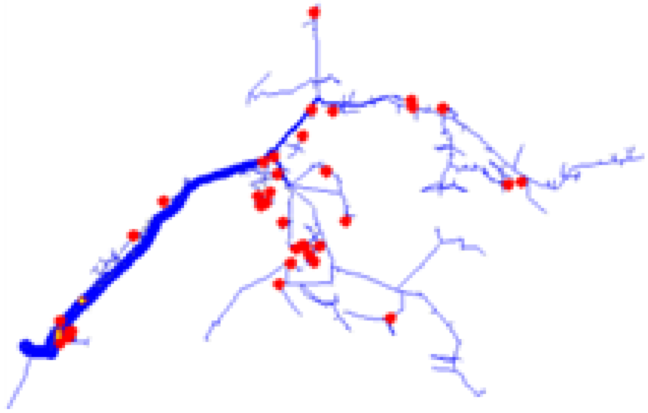


Fig. 3: Feeder topology with the controllable DERs in red.

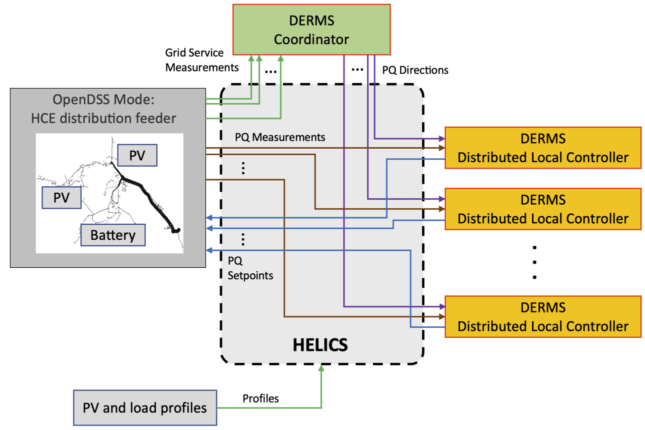


Fig. 4: Co-simulation diagram with HELICS.

brought within their bounds via a minimum response time after the disturbance. With the other uncontrollable loads and generation in the distribution network affecting the value of the grid service measurements, however, the ideal scenario of strictly keeping them within bounds might not be feasible, even for a well-functioning DERMS. Thus, we allow the grid service measurements to have a certain amount of tolerance outside of the grid service bounds and still consider the DERMS functioning.

Bringing a minimum response time and measurement bound tolerance together for a grid service, we label a DERMS as functioning with respect to a specific grid service measurement if it brings the grid service measurement within the tolerance added to its bound within the minimum response time after the disturbance. Finally, we label a DERMS as functioning only if it is functioning for all of its grid service measurements. The specific values of the minimum response time and tolerance can be changed depending on how fast and strict the DERMS is contracted to be.

To illustrate the described metrics, we provide two borderline examples of a VPP grid service in Fig. 2 that is either (a) functioning or (b) not functioning. The tolerance is set at 0.04 MW with a minimum response time of 10 minutes. There are two disturbances, which are step changes in the VPP bounds, occurring at 10:00 and 11:00. In Fig. 2a, the feeder head power measurements stay within the tolerances after both disturbances. In Fig. 2b, however, the measurements barely pass the functionality test after the first disturbance but fail after the second disturbance due to the oscillations outside of the tolerances.

IV. Numerical Evaluation

In this section, we use the metrics described in Section III to find the upper limits on the time resolution of the communication channel categories described in Section II with numerical simulations of a real-world feeder and a primal-dual-based DERMS.

A. Setup

Consider a primal-dual-based DERMS tasked with providing voltage support and VPP grid services for a three-phase distribution feeder. The feeder is modeled on a utility system in Colorado, containing approximately 2,000 nodes, which can attain a peak load of 4.6 MW. The DERs controlled by the DERMS include 163 curtailable photovoltaic (PV) solar generators with smart inverters spread across the feeder (see Fig. 3), of which 140 are colocated with a controllable energy storage battery. Because of their wide spatial distribution, the DERs double as voltage measurement sensors for the voltage support grid service. The PV generators have capacities that range from 0.04 kW to 34 kW, with an average of 10 kW, and the batteries have energy storage capacities that range from 13.5 kWh to 54 kWh, with an average of 19 kWh.

Each PV generator has its own DERMS local controller that also controls the colocated battery, if it has one. In addition to basing the power injection set point of its DER(s) on the received direction signals from the DERMS coordinator, it accounts for the cost of curtailment of a PV generator from its available power and the cost of the battery's state of charge deviating from its set preference. Both costs are modeled by quadratic functions, scaled by the inverter rating in the case of a PV generator and are scaled by the storage capacity in the case of a battery. More details on the cost models can be found in [4], [7].

The Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) [14] is used to co-simulate all of the system components, including the feeder, the coordinator, and the distributed local controllers. HELICS coordinates the execution timing for each simulation module and the information sent between them; see Fig. 4 for a diagram of the information being exchanged among the system components through HELICS. The real-world feeder is simulated as a quasi-steady-state time series in OpenDSS every 2 seconds, and the DERs are simulated as part of the feeder model. The DERMS coordinator updates its internal variables every 1 minute based on the grid service measurements it receives from the feeder. The local controllers update their interval variables at the same time resolution that they communicate

Communication Channel Category	Time Resolution Upper Bound	Limiting Grid Service
Grid service measurements to DERMS coordinator	2 minutes	Voltage support, VPP Phase B
DERMS coordinator to local controllers	2 minutes	Voltage support
Local controller and DER(s)	2 minutes	Voltage support, VPP Phase C
All together	2 minutes	Voltage Support, VPP Phase C

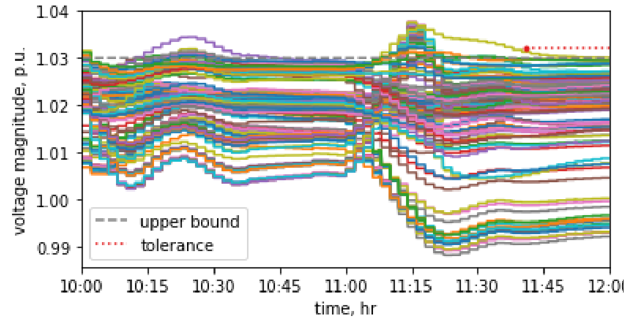
TABLE I: Upper Bounds on the Commmunication Time Resolution

with the DER(s), based on the power injection measurements they receive from the feeder and direction signals they receive from the coordinator. The load and PV generation data were provided by the utility from their advanced metering infrastructure, with the loads changing every 15 minutes, and the PV generation changing every 1 minute.

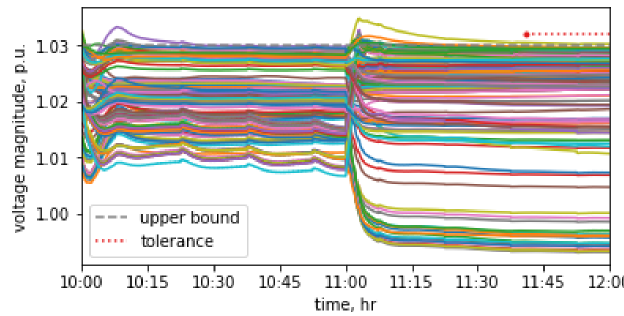
In this study, we evaluate the time resolution of each communication channel category individually while holding all the others at their default settings. Additionally, we evaluate all three categories together by increasing their time resolutions to the same amount. The default time resolution for all categories is 2 seconds. The specific scenario to evaluate the functionality of the DERMS is chosen to be on a day (4/3/19) and time (10 am–12 pm) that has a smooth PV and load profile to limit the effects of exogenous volatility on the DERMS control actions compared to the controlled disturbances we implement for the DERMS evaluation. The disturbance that we implement is a step change in the VPP bound settings at 11 am because the DERMS will need to try to track that change while simultaneously keeping the voltage magnitudes within their bounds. The VPP bounds are defined as ± 0.01 MW from a time-varying VPP set point. At 11 am, the VPP set point changes from 0.97 MW to 1.17 MW for Phase A, from 0.93 MW to 0.70 MW for Phase B, and from 0.95 MW to 0.61 MW for Phase C. Although there is an initial disturbance at 10 am due to the initial grid service measurements being outside of their bounds, we will focus only on the 11 am disturbance for the determination of functionality. The voltage support lower and upper bounds are set at a constant 0.95 p.u. and 1.03 p.u., respectively. The evaluation metrics described in Section III have tolerances set as 0.02 MW for the VPP grid service and 0.002 p.u. for the voltage support grid service under a minimum response time of 40 minutes.

B. Results

The upper bounds for the communication time resolutions for all communication channel categories, individually and together, were found to be 2 minutes (see Table I); however, the VPP grid service measurements that limit them from having a larger time resolution bound are different for each category. On the other hand, they all share the fact that the voltage support grid service also limits them from having a higher time resolution.

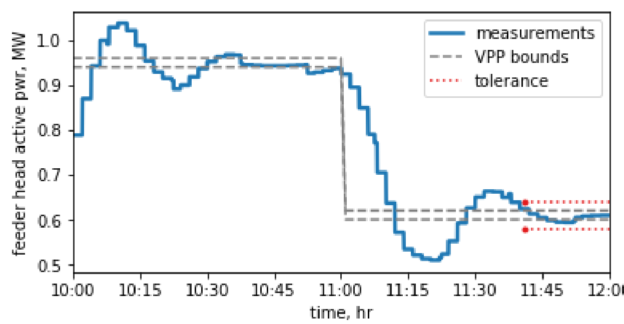


(a) Two-minute time resolution

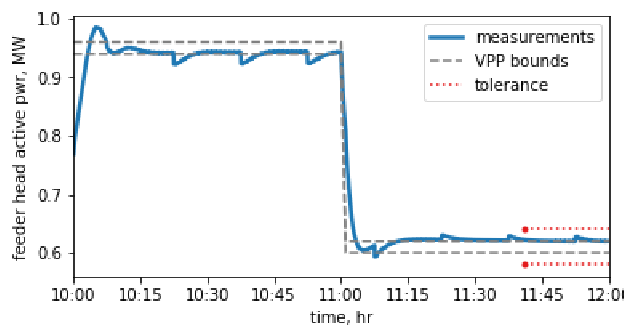


(b) Two-second time resolution

Fig. 5: Voltage magnitudes under different time resolutions applied to all three categories of communication channels.



(a) Two-minute time resolution



(b) Two-second time resolution

Fig. 6: VPP Phase C under different time resolutions applied to all three categories of communication channels.

The behavior of the of the first two categories are almost identical because they are directly related to the communication of the grid service bound violation information. The increase in the time resolution of these two categories simply slows down and stretches out the shape of the grid service measurements, whereas increasing the time resolution of the communication channels between the local controllers and the DERs adds low-frequency oscillations to the grid service measurements. When increasing the time resolution of all three categories together, it is the behavior of the third category that dominates. Figures 5 and 6 show the limiting grid services when increasing the time resolution of all three categories together to 2 minutes and compares them against using the original assumed time resolution of 2 seconds for all categories. With a time resolution of 2 seconds, the minimum response time could be reduced to 5 minutes. But if the minimum response time is 40 minutes, then a time resolution of 2 minutes is sufficient.

C. Discussion

The results show that the communication time resolution for a primal-dual-based DERMS in all three communication channel categories can be increased from seconds to minutes; however, the upper bound on the time resolution is directly related to the metrics that evaluate the functionality of the DERMS. Specifically, our choice of using 40 minutes as the minimum response time means that the DERMS under a time resolution of 2 minutes gets, at most, 20 full control action iterations to respond to a measured or induced disturbance.

For a DERMS that is tasked with providing grid services with a minimum response time smaller than the one used in this study, a balance would need to be made between the benefit of having a faster response time and the potential increased cost of the communication infrastructure needed to give a smaller time resolution because decreasing the minimum response time would decrease the upper bound on the time resolution.

V. Conclusion

This paper studied the communication time resolution bounds among the system components for primal-dual-based DERMS with the intention of informing the DERMS industry about the necessary time resolution of the communication infrastructure. A metric based on the minimum response time after a disturbance was designed to evaluate the functionality of a DERMS with respect to the grid services it is tasked to provide. Numerical simulations with a real-world feeder and load data show that the time resolution can be increased from seconds to 2 minutes when using a minimum response time of 40 minutes. This means that the time resolution specification for the communication infrastructure of primal-dual-based DERMS should be chosen based on the required minimum response time for the grid services. Possible future directions of this work include studying the effects of other communication issues on DERMS, such as time delays, packet loss, or link failures, testing them on a testbed with hardware, and developing a theoretical analysis for time related aspects for DERMS.

Acknowledgments

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office Award Number TCF-21-25008. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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