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Distributed Energy Resource Management System (DERMS) Control Architecture for Grid Services in the Distribution and Bulk Power Systems

DERMS Control Architecture, Conceptual Design, and Communication Requirements to Enable Grid Services from Behind-the-Meter Distributed Energy Resources

2021 TECHNICAL REPORT

Distributed Energy Resource Management System (DERMS) Control Architecture for Grid Services in the Distribution and Bulk Power Systems

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NOTE

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ABSTRACT

This report serves as a distributed energy resource (DER) management systems (DERMS) architecture design guideline to enable behind the meter (BTM) DERs to provide grid services in distribution and/or bulk power systems. The context for the development of this document is a three-year project titled *Enable Behind-the-meter DER-provided Grid Services that Maximize Customer and Grid Benefits (ENGAGE)*. This EPRI led collaborative research project is funded by the U.S. Department of Energy (DOE) through the Solar Energy Technologies Office (SETO) office.

The report provides a multi-layer hierarchical control architecture that enables groups of aggregated DERs to provide services in the bulk power system and/or the distribution system: individual DERs located BTM grouped together via a Local DERMS, and multiple local DERMS subsequently grouped together via an aggregator DER management system. The report is organized as follows: Chapter 2 provides an overview of the control architecture needed for BTM DER to provide grid services; Chapter 3 explains the control architecture and design needed for the first layer of control where a local DERMS manages a group of DER; Chapter 4 provides the functionality and control design when an aggregator manages a group of local DERMS; and Chapter 5 explains the communication requirements needed for providing grid services to the distribution and/or bulk markets.

Keywords
Distributed Energy Resource (DER)
Local DER Management System
Aggregated DER Management System
Distribution Grid Services
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EXECUTIVE SUMMARY

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PRIMARY AUDIENCE: Distribution Utilities, DERMS vendors, and DER owners

SECONDARY AUDIENCE: Policymakers, Project Developers, Energy Regulatory Agencies

KEY RESEARCH QUESTION

This report provides control design and architecture guidance for DERMS that enables aggregated groups of distribution-connected distributed energy resources (DERs) to participate in the distribution and bulk power system (BPS) grid services opportunities.

RESEARCH OVERVIEW

The report provides a multi-layer hierarchical control architecture that enables groups of aggregated DERs to provide services in the bulk power system and/or the distribution system: individual DERs located BTM grouped together via a Local DER management system and multiple local DERMS are subsequently grouped together via an aggregator DER management system.

The report is organized as follows: Chapter 2 provides an overview of the control architecture needed for BTM DER to provide grid services; Chapter 3 explains the control architecture and design needed for the first layer of control where a local DERMS manages a group of DER; Chapter 4 provides the functionality and control design when an aggregator manages a group of local DERMS; and Chapter 5 explains the communication requirements needed for providing grid services to the distribution and/or bulk markets.

KEY FINDINGS

- Need for a control architecture when multiple DER are providing services to distribution and/or bulk power systems.
- Need for multi-layer hierarchical control architecture to enable aggregated DERs participation in the market
- Definition of the control design and logic for a hierarchical control architecture
- Communication and messaging requirements to efficiently provide services in the market

WHY THIS MATTERS

As the penetration level of DERs increases, grid operators are evaluating new opportunities for DERs to provide value to the electricity grid. In order to provide grid services a control architecture and logic needs to be defined and evaluated for DER aggregator to efficiently manage its resources (local DERMS or a directly managed DER).

HOW TO APPLY RESULTS

This report serves as a control design guide to DERMS developers to enable aggregated DERs participation in the distribution and/or bulk power system. It also summarizes the communication and messaging requirements for a hierarchical control architecture.

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PROGRAM: DER Integration, Program P174

DEFINITIONS

Distributed energy resource (DER): a resource interconnected to the electric grid, in an approved manner, at or below IEEE medium voltage (69 kV), that: generates electricity using any primary fuel source; and/or stores energy and supplies electricity from that reservoir; and/or involves load changes undertaken by end-use customers specifically in response to control signals, prices or other market-based inducements.

Controllable loads: electric loads whose energy consumption schedule can be planned ahead of time by end-users, or changed in response to control signals, prices or other types of inducement. Examples of controllable loads include heating, ventilating, and air conditioning (HVAC) systems, water heaters, pool pumps, or electric vehicle charging stations.

Aggregated availability (for a group of DER): refers to the capability of a group of DER managed by a DER management system (DERMS) to adjust (increase or decrease) the aggregated real or reactive power levels for the whole group. The aggregated availability of a given group of DER may be determined for the present time or forecasted for a future time. For a given time, the aggregated availability may be defined in terms of the maximum and minimum power levels that the DER group could adjust to, and the rate at which this change could take effect. This document does not intent to determine *how* the aggregated availability is effectively calculated.

Dynamic resource allocation: functional module of the DERMS; runs a scheduling algorithm solving an optimization problem over a receding time horizon.

Local DERMS (L-DERMS): entity managing a group of DER devices to respond to real and reactive power requests and setpoints by an upstream managing entity while meeting local constraints and satisfying local objectives as appropriate.

Aggregator DERMS (A-DERMS): a group managing entity that manages a group of L-DERMS/DER devices to respond to real and reactive power requests and setpoints by an upstream managing entity like independent system operator(ISO) and/or distribution system operator (DSO) while meeting its constraints and satisfying objectives as appropriate.

Operating range: for a given variable, pair of values that define a numerical interval where the value of the variable should be maintained. The operating range may be time-specific and defined over a multi-period time horizon.

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INTRODUCTION

As the penetration level of distributed energy resources (DER) increases, grid operators are evaluating new opportunities for DERs to provide value to the electricity grid. This includes grid services provided by DERs located behind the retail meter (BTM) through DER aggregators.

This document presents a multi-layer hierarchical control architecture enabling groups of aggregated DERs to provide services in the bulk power system and/or the distribution system:

- Individual DERs located BTM are first grouped together via a Local DER management system (L-DERMS);
- Multiple L-DERMS are subsequently grouped together via an aggregator DER management system (A-DERMS).

The aggregator offers grid services to the distribution utility and/or wholesale market operator. The role of the A-DERMS is to disaggregate the service requirements across all L-DERMS and/or standalone DERs it manages. All control interactions are enabled by contractual agreements between each local customer with DERs and the aggregator, and between the aggregator and the service requesting entity (distribution utility and/or wholesale market operator). The control architecture, logic, communication requirements and message exchanges presented in this document were developed to meet the grid service requirements documented in a companion report[1].

The context for the development of this document is a three-year project titled "Enable Behind-the-meter DER-provided Grid Services that Maximize Customer and Grid Benefits (ENGAGE)". This EPRI-led collaborative research project is funded by the U.S. Department of Energy (DOE) through the Solar Energy Technologies Office (SETO) office.

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[1] *Grid Services in the Distribution and Bulk Power Systems: A Guideline for Contemporary and Evolving Service Opportunities for Distributed Energy Resources.* EPRI, Palo Alto, CA: 2021. 3002022405.

2
CONTROL ARCHITECTURE

This chapter describes the overall conceptual design of the proposed DER Management System (DERMS) control architecture.

Background

Distributed energy resources (DER) located behind the retail meter (BTM) have the potential to provide grid services to the distribution system and/or bulk power system. BTM resources may provide grid services as standalone resources, or more likely as part of an aggregated group of DERs considering that BTM resources are typically smaller in size. Multiple BTM resources located behind the same retail meter may be able to provide grid services concurrently. Participation eligibility depends on resource size, and the participation threshold(s) defined for each grid service.

This document focuses more specifically on the case where BTM resources are too small to provide grid services as standalone resources, and aggregate in order to reach a certain “critical mass” and meet, as a group, the participation requirements. Such aggregation of smaller DERs providing services as a group results in a hierarchical control architecture, where managing entities (higher in the hierarchy) are supervising managed entities (lower in the hierarchy).

In this document, the terms “managing entity” and “managed entity” are defined as follows:

- Managed entities respond to service requests and control signals received from a managing entity (higher in the control hierarchy). Managed entities can be individual DER assets, or a DERMS managing a group of several resources.
- Managing entities coordinate a portfolio of managed resources. Managing entities are equipped with control algorithms that coordinate their portfolio of managed entities.

Some entities, such as A-DERMS, can simultaneously be a managed entity and a managing entity: as managed entity, they offer services to a higher-level managing entity upstream; as managing entity, they are coordinating a portfolio of resources downstream.

The control interactions between managed and managing entities are typically enabled by contractual agreements specifying the obligations of the managed entities towards the managing entities, and other aspects related to financial compensation and settlement.

Approach

One key objective of the *ENGAGE* project is to design, develop, and demonstrate a multi-level control architecture enabling an A-DERMS to manage a group of resources consisting of standalone DERs and/or L-DERMS themselves managing individual DERs. The goal is to enable A-DERMS to offer grid services to the distribution system operator[2] (DSO) and/or independent system operator[3] (ISO).

Therefore, A-DERMS and L-DERMS are fundamental components of the proposed control architecture. Downstream, the A-DERMS exchanges information and control signals with one or several L-DERMS and/or standalone DERs. Upstream, the A-DERMS receives grid service requests from a DSO and/or ISO acting as managing entities for the A-DERMS.

Each L-DERMS can communicate downstream with the DERs it manages. In this document, three types of DERs are considered: solar PV, energy storage and controllable loads. "Controllable loads" refers to electric loads whose energy consumption schedule can be planned ahead of time by end-users, or changed in response to control signals, prices or other types of inducement. Examples of controllable loads include HVAC systems and electric water heaters.

Similarly, the A-DERMS can communicate downstream with multiple L-DERMS and/or standalone DERs. The A-DERMS also has in-built disaggregating algorithms that distribute grid service requirements set at the aggregation level among the L-DERMS and/or DERs it manages. The A-DERMS does *not* have visibility into the resources managed by individual L-DERMS that it controls: the capabilities of these DER devices are aggregated by the L-DERMS into group-level services (e.g. kW limits) that the A-DERMS can call upon.

The hierarchical approach described above reduces the complexity of the underlying control and optimization problems to be solved in order to enable BTM DERs to provide grid services. Instead of having to interface with a myriad of smaller DERs, the DSO and/or ISO simply interact with DER Aggregators through an A-DERMS, which itself interacts with a set of L-DERMS and/or larger standalone DERs.

Hierarchy between Control Levels

A-DERMS and L-DERMS have their own operational objectives and execute specific control strategies to reach these objectives. These strategies are implemented in the form of control algorithms that govern each controllers' actions.

Although the architecture described in this document includes only three layers of control, the research developed in this project can be extended to include additional control layers, as shown in Figure 1.

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[2] While the term distribution system operator (DSO) is often used in ongoing discussions related to grid modernization, the utility industry has not yet converged to a universally accepted definition. This report does not intend to set such definition: the term DSO is used broadly to refer to a traditional distribution utility that has implemented new functional capabilities to manage a high-DER distribution system, and enable DERs to provide grid services.

[3] The term independent system operator (ISO) is also used broadly in this report to refer to the wholesale market operator, and includes adjacent terms such as regional transmission organization (RTO) or transmission system operator (ISO).

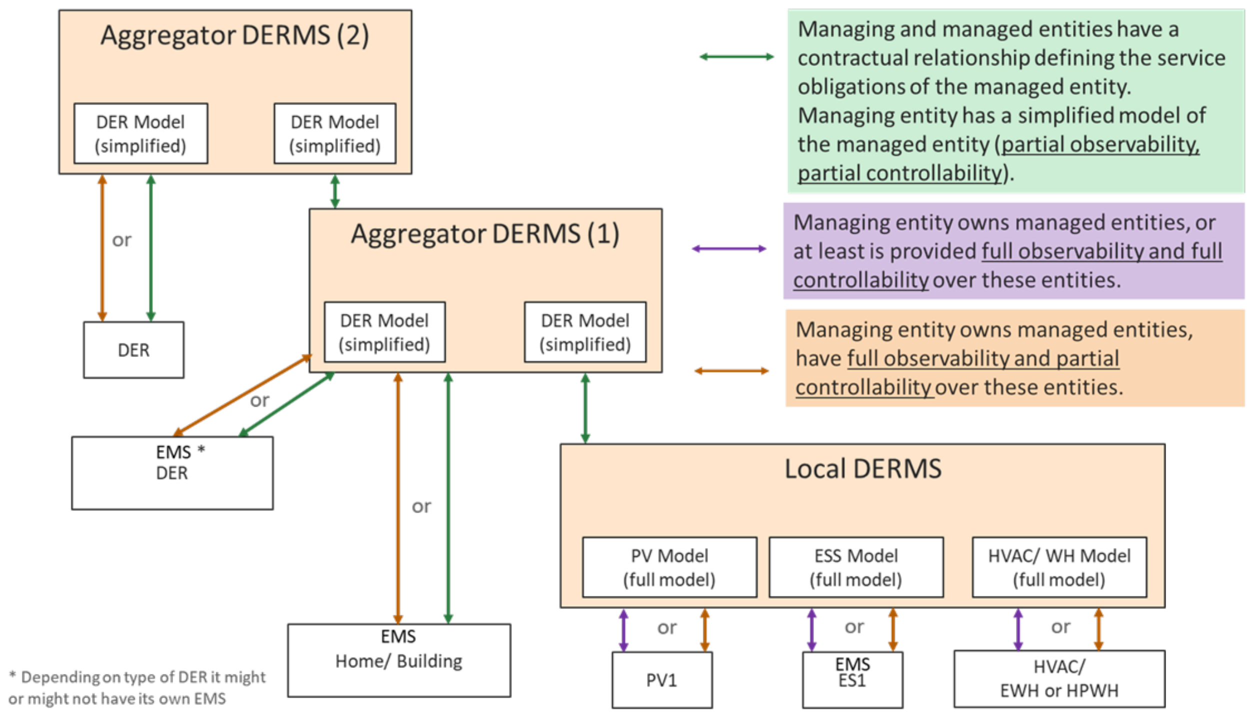

Figure 1. Conceptual Control Architecture Illustrating Three Types of Relationships Between Managed and Managing Entities.

Hierarchy types

There can be different levels of *observability* and *controllability* between managing and managed entities. The approach selected is reflected in the contractual agreement established between these entities.

In this document, *observability* refers to the level of knowledge and visibility the managing entity has over the managed entity. This includes off-line information on the state, model or availability of the DER (or mix of DERs) constituting the managed entity, and real-time information on DER status, present P/Q values, etc. Two levels of observability are considered:

- *Full observability*: The managing entity has *complete* knowledge of the DER model, constraints and state characterizing the managed entity.
- *Partial observability*: The managing entity only has *partial* knowledge of the DER, its current state and availability. Under partial observability, the managing entity might only be able to observe a portion of the complete range of available capacity, as defined contractually, while the actual availability of the resource might be higher.

Controllability refers to the extent to which the managing entity can control the managed entity. Two levels of controllability are considered in this document:

- *Full controllability*: The managing entity can send a service request for the complete range of available power of managed entities. The managed entity will follow the incoming power request.

- *Partial controllability*: The managing entity can send a service request for a portion of complete range of available power which is defined contractually. The managed entity will follow the incoming power request.

Table 1 presents three use cases based on varying observability and controllability levels. An example control architecture using the concepts and approach presented above is shown in Figure 2.

Table 1. Three Types of Relationships Between Managed and Managing Entities Based on Different Observability and Controllability Levels.

Use Case	Observability *(of Managing Entity over Managed Entity)*	Controllability *(of Managing Entity over Managed Entity)*	Comments	Example
1	Partial	Partial	Managing entity may have some observability (status, present P/Q values, etc.), and can only send commands within range of managed entity's obligations defined contractually, which may be less than the actual capabilities of the managed entity.	Energy storage (Managed entity) providing capacity deferral to DSO (Managing entity) every day from 12pm to 3pm. ES only reports status (online/offline) and present P value. DSO can only send command within a certain range agreed upon contractually.
2	Full	Partial	Managing entity has full observability over the managed entity (most likely a standalone resource), but can only send commands within range of managed entity's obligations defined contractually.	PV inverter vendor (Managing entity) has full observability over fleet of PV inverters in each region (managed entities). However, vendor can only send curtailment commands within a certain range agreed upon contractually.
3	Full	Full	Managing entity has full observability and full controllability over managed entity.	L-DERMS (Managing entity) has full observability and controllability over PV inverter (Managed entity).

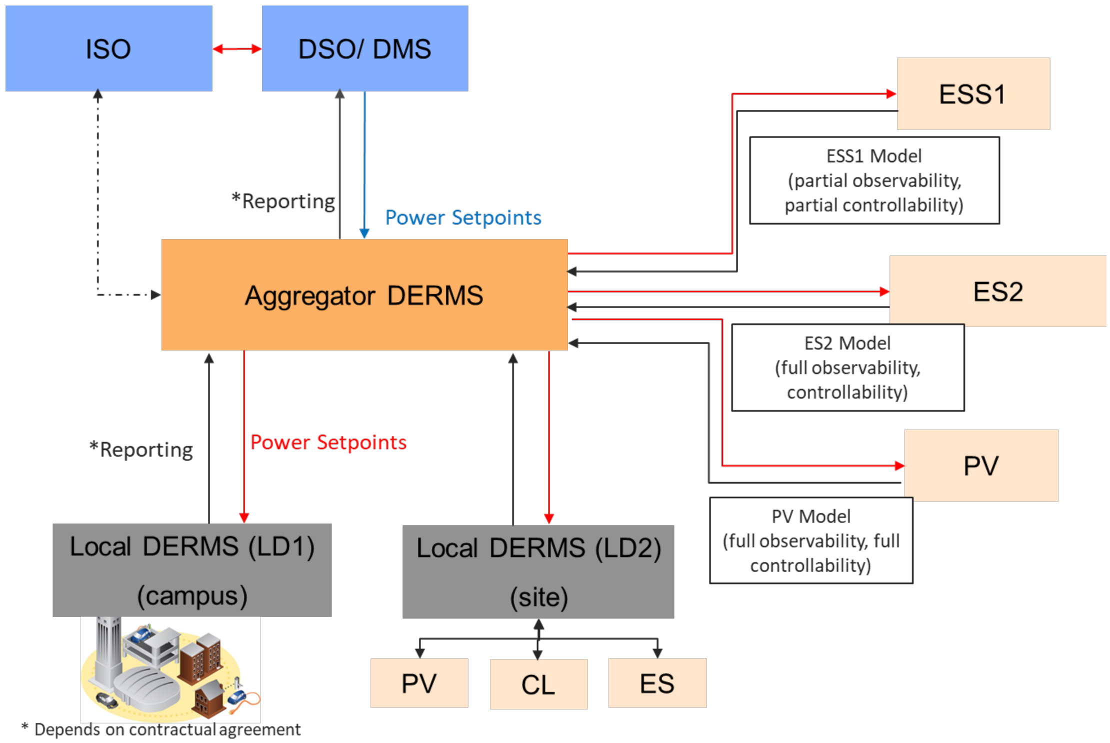

Figure 2. Example Control Architecture with Varying Observability and Controllability

Local DERMS (L-DERMS)

L-DERMS manages one or several DERs located behind the same utility meter. The L-DERMS coordinates this group of DERs in response to incoming service requests from a higher-level managing entity (for example, an A-DERMS), as well as local control objectives assigned to the L-DERMS. This report assumes, as shown in Figure 1, that each L-DERMS has full observability over the DERs it manages, and may have partial or full controllability over these DERs, depending on the scenario. Each L-DERMS receives service requests from a higher-level managing entity guiding grid service delivery by the L-DERMS.

In this project, model predictive control (MPC) based look-ahead optimization is used by the L-DERMS to dispatch the DERs it manages. This optimization problem considers the set of constraints modeling each DERs (as defined in Appendix), power constraints (modeling the requests received from the higher level managing entity) and other local optimization objective(s) assigned to the L-DERMS. The L-DERMS has access to a complete (full controllability) or simplified (partial controllability) model of each of the DER it manages, depending on the scenario. Since MPC is a look-ahead optimization approach (“Plan and Do”), forecast of DER availability is also provided as an input to the optimization problem.

The optimization objective of the L-DERMS incorporates cost functions associated with each DER it manages, which may represent actual operating costs, or simply dispatch preferences. For example, a battery may be available for dispatch only during few hours of the day, and it is preferred that the battery should not get dispatched during later parts of the day. This information is used by the MPC algorithm to optimally dispatch all DERs managed by the L-DERMS.

Once an optimal solution is selected, the L-DERMS continues the coordination of the local resources it manages based on its revised plan/targets. The L-DERMS reports the current state and planned power profiles to the managing entity it reports to, for example an aggregator, as appropriate based on their contractual agreement.

Figure 3 represents an example architecture with an L-DERMS managing two DERs: PV, and storage managed by a managing entity.

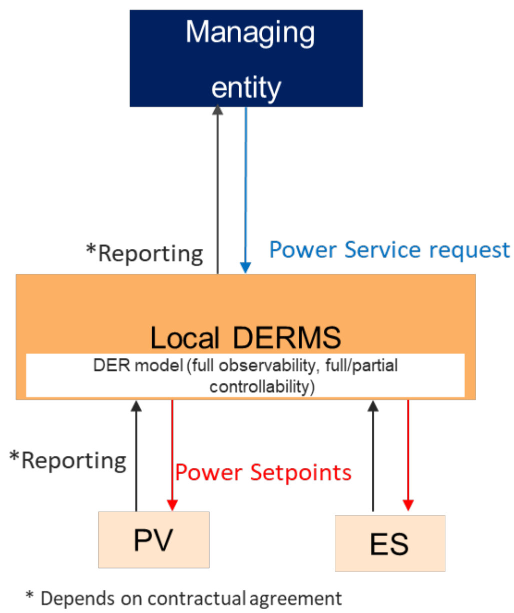

Figure 3. Control Architecture

Each L-DERMS manages a group of DERs to respond to the real and reactive power requests sent by an A-DERMS while being able to meet its *local constraints* and satisfying *local objectives* (including satisfying local energy needs) as appropriate.

The *local objective(s)* and constraints assigned to the L-DERMS are defined by the DER group owner and may include one or several of the following elements:

- Ensure all or some of the local energy needs are met;
- Ensure requirements of service requesting entity are met;
- Maximize economic benefit of the DER group owner;
- Meet environmental goals by maximizing renewable resource utilization.

The exact formulation of the local objective shall be specific to each DER group, and dependent on each implementation. This is discussed more in detail in Chapter 3.

Aggregator DERMS (A-DERMS)

The A-DERMS is the managing entity that coordinates a portfolio of standalone DER assets and/or other DERMS (which themselves manage their own resource portfolio) –this could include L-DERMS or other A-DERMS. A-DERMS itself provides grid services to another, higher-level managing entity (e.g. DSO, ISO). It is therefore responsible for disaggregating the power requests received from the higher-level managing entity, and dispatch downstream power requests to DERs and/or DERMS it manages. Depending on the contractual agreements between the aggregator and the various resources it manages, A-DERMS may be able to dispatch these resources fully or partially.

An A-DERMS can be utility-owned or third party-owned. One particular type of third party aggregators are DER vendors, for example PV inverter manufacturers, offering customers purchasing their products an opportunity to aggregate in exchange for some form of financial compensation. Customer acquisition efforts to build portfolio of aggregated DERs, especially smaller scale DERs, are usually time consuming and costly. This explains in part why the utility industry has been exploring the option of working with third party aggregators who can take responsibility for customer acquisition and assemble DER portfolios at strategic locations where grid services are in demand.

The A-DERMS can be part of many different architectures. Figure 4, Figure 5 and Figure 6 provide three example cases:

- Case 1 (Figure 4): A-DERMS that manages a L-DERMS and a standalone DER resource;
- Case 2 (Figure 5): A-DERMS that manages two local DERMS and a standalone DER resource;
- Case 3 (Figure 6): A-DERMS that manages (*n*) number of local DERMS and DER resources aggregated together.

Assume an illustrative example where the A-DERMS receives a request from its managing entity to provide 1MW (either injecting 1MW, reducing demand by 1MW, or a combination of both resulting in a net change of 1MW). In Case 1, the A-DERMS could use the maximum generation available power of PV at 500kW and get the remaining 500kW from the L-DERMS. In Case 2, for the same request, the A-DERMS could choose to request 500kW from the PV resource, 400kW from the first L-DERMS, and the remaining 100 kW from the second L-DERMS.

In practice, the dispatch selected by A-DERMS depends on the request received from the higher level entity, the control and optimization objectives, and availability of the resources managed by A-DERMS (L-DERMS, standalone DER, and/or other A-DERMS). Chapter 4 provides further considerations on controls and optimization aspects for A-DERMS.

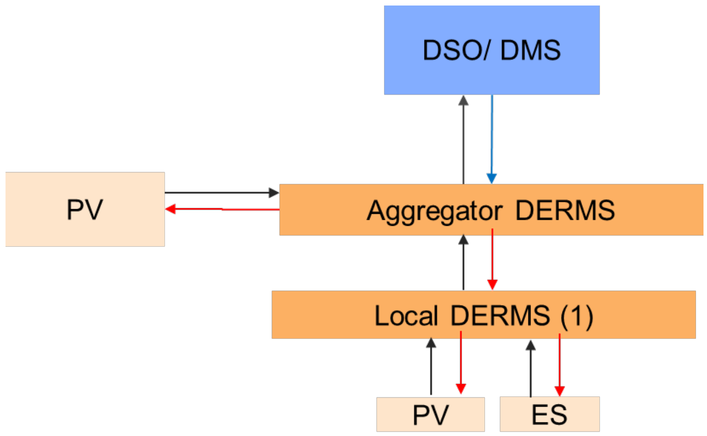

Figure 4. Case 1: A-DERMS with One L-DERMS and One DER Resource

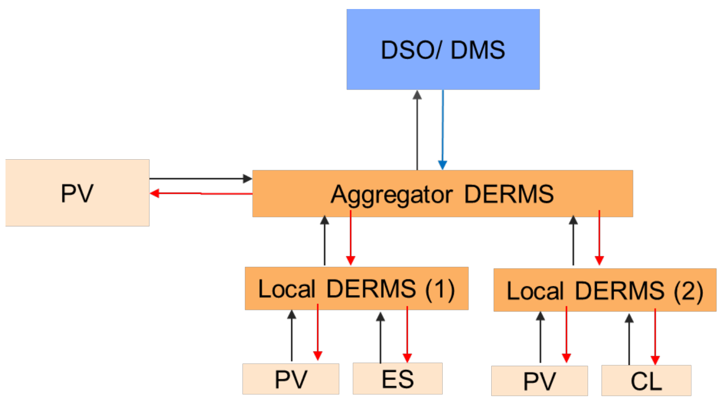

Figure 5. Case 2: A-DERMS with Two L-DERMS and One DER Resource

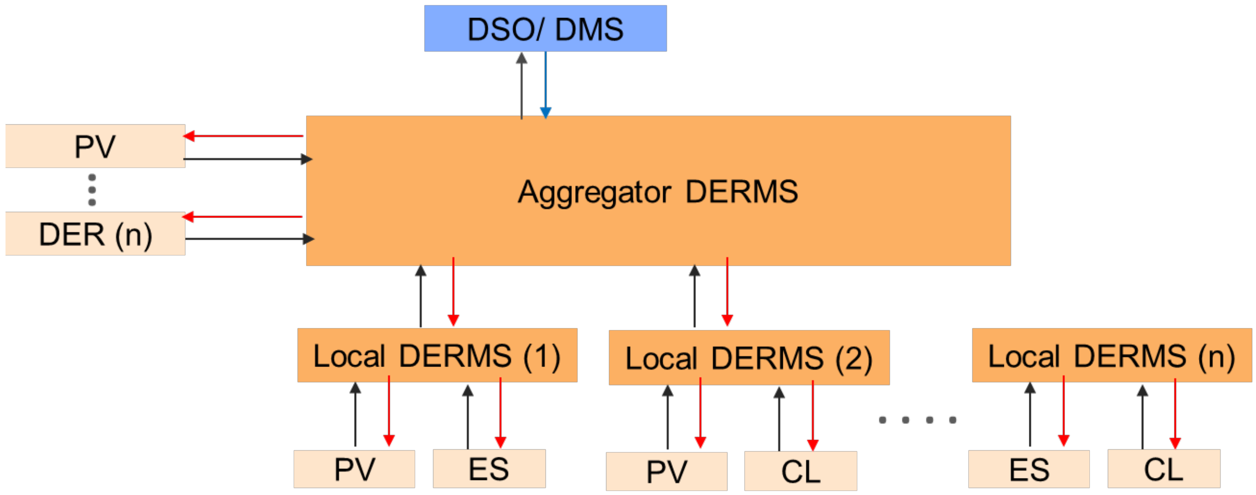

Figure 6. Case 3: A-DERMS with Multiple L-DERMS and DER Resources

Categories of relationship between components

Table 1 introduced several types of possible relationships between managed and managing entities, based on different levels of observability and controllability.

This report makes the following assumptions:

- Relationship between DSO/ISO (managing entity) and A-DERMS (managed entity): the DSO/ISO has *partial observability* and *partial controllability* over A-DERMS. The specifics are defined contractually between the parties.
- Relationship between A-DERMS (managing entity) and L-DERMS/other resources (managed entities): three combinations are possible:
    - Full observability / Full controllability
    - Full observability / Partial controllability
    - Partial observability / Partial controllability

Another important aspect relates to whether A-DERMS is providing a service to the DSO/ISO that requires "booking" aggregator capacity.

For a service that requires *booking* aggregator capacity, the DSO/ISO reserves capacity with the aggregator, and the aggregator commits to provide the service when called upon. This obligation is contractual, and the aggregator would likely be penalized if unable to perform when called upon. Chapters 3 and 4 discuss the objective and constraints needed for managing the aggregator's portfolio in order to ensure service requirements are satisfied. Post-settlement compensation and/or penalties payed by the aggregator in case of any violations are out of the scope of this report.

For a service that does *not* require booking aggregator capacity, the DSO does not reserve capacity with the aggregator ahead of time. Instead, A-DERMS may respond to the service opportunity "on the spot". Therefore, A-DERMS is not bound to provide the service when called upon, unless it agrees to respond to the opportunity.

The rest of this document primarily focuses on services *with booking*, i.e. cases where the managing entity (e.g. DSO, ISO, A-DERMS) has booked capacity ahead of time through an agreed upon contract with a managed entity (e.g. A-DERMS, L-DERMS).

3
LOCAL DERMS MANAGING A GROUP OF DER

This chapter focuses on the first layer of control where a local DERMS manages a group of DERs.

Each L-DERMS manages a group of DER devices. This report assumes that all DERs managed by a L-DERMS are located behind the same revenue meter. L-DERMS manages DERs in order to respond to real and/or reactive power requests sent by an upstream managing entity (e.g., A-DERMS, DSO, ISO). The goal of L-DERMS is to respond favorably to the requests coming from its managing entity while meeting its *local constraints and objectives*, as appropriate. While this chapter focuses on the control interactions between L-DERMS and the DERs it manages, the next chapter considers the control layer immediately above, where the A-DERMS manages a portfolio of L-DERMS.

The rest of this chapter considers four example cases involving a L-DERMS managing DERs. Two parameters were considered to develop these examples:

- Booking: is the L-DERMS providing a service with or without booking to the upstream entity?
- Controllability: does the L-DERMS have full or partial control over the DERs it manages?

For all four cases, the L-DERMS has full observability over the DERs it manages. Table 2 provides a summary of the four cases considered.

Table 2. Four Example Cases Considered

Case	Booking	Observability	Controllability
A	✓	Full	Full
B	✕	Full	Full
C	✓	Full	Partial
D	✕	Full	Partial

In Case A, shown in Figure 7, L-DERMS has full observability and controllability over the resources it manages. L-DERMS provides a service “with booking” to its managing entity, i.e. the L-DERMS reserves capacity to ensure a response if called. Once called, the L-DERMS dispatches the service request across the resources it manages. The control objectives and constraints governing how the L-DERMS is dispatching the request are defined below.

Case A: L-DERMS providing a service "with booking", and with full observability and controllability over the resources it manages

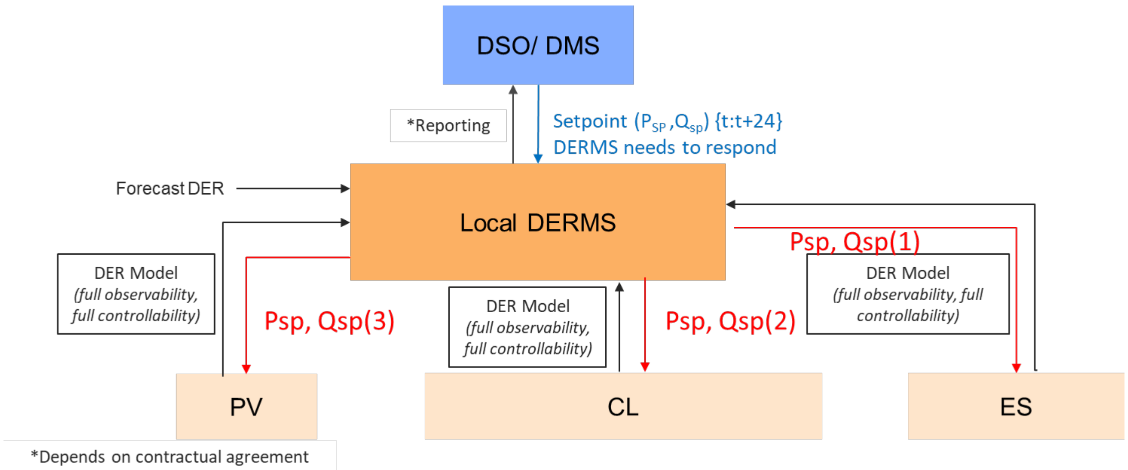

Figure 7. L-DERMS Providing a Service with Booking, with Full Observability and Full Controllability Over the Resources it Manages

L-DERMS Objective

Minimize {Service deviation penalty + DER utilization cost + Retail electricity charges}

The three elements constituting the L-DERMS objective function are each defined as follows:

- *Service deviation penalty* component models the penalty that would be incurred by the L-DERMS, should it fail to provide the grid service(s) as promised to the managing entity (e.g. A-DERMS, DSO).

  The Service deviation penalty is defined as: $A * (\delta_p + \delta_q)$

  where: δ_p is the real power service request deviation slack
  δ_q is the reactive power service request deviation slack

  The slack parameters (δ_p, δ_q) represent the difference between the capacity requested by the managing entity and the net capacity effectively delivered by the L-DERMS. Ideally, this difference should be zero (i.e. the L-DERMS is delivering exactly what the managing entity has requested).

  The coefficient $\boldsymbol{A}$ is associated with the service penalty and is typically defined as a large value, reflecting that any deviations from the service requirements should be avoided. When the contractual agreement between the L-DERMS and the managing entity specifies a penalty schedule, the value selected for the $\boldsymbol{A}$ coefficient may reflect that schedule.[4]

- *DER utilization cost* models the cost associated with dispatching each DER. This element of the objective function implicitly defines which DERs should be dispatched first by the L-DERMS.

  The DER utilization cost is defined as: $\sum_{\mathrm{i}=0}^{\mathrm{N=number\ of\ DER}} \mathrm{B_i} \ * \ \mathrm{DER\ attribute_i}$

  where: $\mathrm{B_i}$ is a coefficient representing the priority at which DER *i* should be dispatched
  $\mathrm{DER\ attribute_i}$ is a parameter reflecting how much DER *i* is being dispatched

  If all DERs hold the same priority, then the value of the coefficients $\mathrm{B_i}$ will be uniform across all DERs. Otherwise, the DERs which should be dispatched last will tend to have larger $\mathrm{B_i}$ values.

  For example, if L-DERMS is managing PV and ES, and it is preferred that PV be dispatched to its maximum availability first before ES is asked to discharge, then the $\mathrm{B_i}$ coefficient associated with the ES utilization would be set higher (to minimize its usage) than the coefficient associated with PV utilization (to maximize its usage).
  $\mathrm{DER\ attribute_i}$ may be defined differently depending on the DER type considered. For example, for a battery storage system, the utilization cost may be primarily associated with its degradation cycles; the DER attribute parameter may therefore be set to reflect the number of charge/discharge cycles, which the optimization problem would seek to minimize.

  - *Retail electricity charges* component models the electricity cost to the DER group managed by the L-DERMS, assessed at the point of connection with the grid. All the DERs managed by the L-DERMS are assumed to be behind the same revenue meter.

  The Retail electricity charges are defined as :

  $$C * Total\ power\ exchanged\ at\ point\ of\ connection\ of\ revenue\ meter$$

  This element of the objective function reflects that one of the goals pursued by the L-DERMS is to minimize the total retail electricity charges for the DER group it manages. These charges depend on the tariff rate structure (reflected in the coefficient $\boldsymbol{C}$), and the amount of power exchanged with the grid.

  The total amount of power measured by the revenue meter includes the power delivered by each controllable DERs, and the non-controllable load collocated at the same site and connected behind the same revenue meter.

---

[4] Alternatively, the service requirements can also be modeled using hard constraints in the optimization problem. However, the hard constraint approach may lead to infeasible issues. For this reason, the approach presented in this report favors the penalty factor approach.

L-DERMS Constraints

The mathematical formulation developed considers two types of constraints in the optimization problem solved by the L-DERMS: DER constraints and, Service constraints (on real and/or reactive power).

1. *DER constraints*: These constraints represent the mathematical model of each of the DERs managed by the L-DERMS. The DER models are described in further details in Appendix, and the associated constraints are added to the optimization problem solved by the L-DERMS.

2. *Service constraint*: Each service request is modeled as a soft constraint, where any deviations from the active and/or active power setpoints sent by the managing entity are minimized as part of the objective function (variables δ_p, δ_q defined above):
   - Real power setpoints– the constraint is formulated as:
     $\sum_{i=0}^{i=number\ of\ DER} P_i - P_{baseline} + \delta_p == Psp,\ \ \delta_p \geq 0$
     where: $P_{baseline}$ is the baseline power[5] calculated for the DER group managed by L-DERMS.
     Psp is the real power setpoint request received by L-DERMS from the managing entity.
   - Reactive power setpoints–
     - If all DER managed by the L-DERMS provide reactive power support, the constraint is formulated as:
       $\sum_{i=0}^{i=number\ of\ DER} Q_i + \delta_q == Qsp,\ \ \delta_q \geq 0$
     - If only one DER is predefined to provide reactive power support, the constraint is modeled as:
       $Q_{\mathrm{i}} == Q_{sp}$ where DER *i* is assigned to provide reactive power support

In the formulation adopted in this report, the inverter quadratic operating constraint ($P^2 + Q^2 \leq S^2$) for each inverter-based DER is modeled outside of the optimization problem defined above. This keeps the optimization problem formulation linear, which is generally easier and faster to solve. It is assumed that all inverters run in Q-priority mode. Every time the optimization problem is solved, the solution variables corresponding to the real power dispatch of each DER is revaluated to ensure that $P^2 + Q^2 \leq S^2$ is verified for each inverter.

The objective function and set of constraints described above form the optimization problem solved by the L-DERMS, following a model predictive control (MPC) approach: the problem is solved for the next *T* time intervals, and the L-DERMS plans to dispatch the DERs it manages according to the solution selected. However, only the dispatch setpoints for the first time-interval

---

[5] This baseline is the power profile of the DER group managed by the L-DERMS, as measured at the utility meter. This baseline calculation is based on past behavior of the specific L-DERMS. In this report, it is assumed that the baseline calculation includes the controllable DERs managed by the L-DERMs, and all other non-controllable assets co-located behind the same meter.

is actually sent to the DERs. The entire problem is then re-run prior to entering the next time interval.

Once the setpoints for the next immediate time interval are sent to the DERs, a fast feedback control loop continuously tracks for any deviations between the forecasted values assumed in the MPC framework, and the real time evolution of these variables. This fast feedback control can be carried out in multiple ways:

- *Redispatch of a single, pre-assigned DER*: when deviations from forecasted values are observed in real time, a pre-assigned DER is re-dispatched to close the gap between forecasted and real-time values.
- *Redispatch all DER*: all DER dispatch setpoints are revaluated using an optimization-based logic when deviations between forecasted and real-time values are observed.

The second approach, requiring a full re-solve of the optimization problem, may generate significant time delays in producing an updated response, which might be inadequate with the respond time requirements of the service being delivered. For this reason, this report solely focuses on the first approach, assuming that one of the DERs managed by the L-DERMS has been pre-assigned to address real-time deviations.

In Case B, shown in Figure 8, L- DERMS has full observability and controllability of the DERs it manages. L-DERMS provides a service "without booking" to its managing entity, i.e. L-DERMS does not commit to reserve capacity and respond to requests from the managing entity. However, the managing entity may still send a request; then, L-DERMS has the option to respond (or not) depending on its present availability and other local objectives. If L-DERMS chooses to respond, it then commits to deliver. Case B is further discussed in Appendix.

Case B: L-DERMS providing a service "without booking", and full observability and controllability of the resources it manages

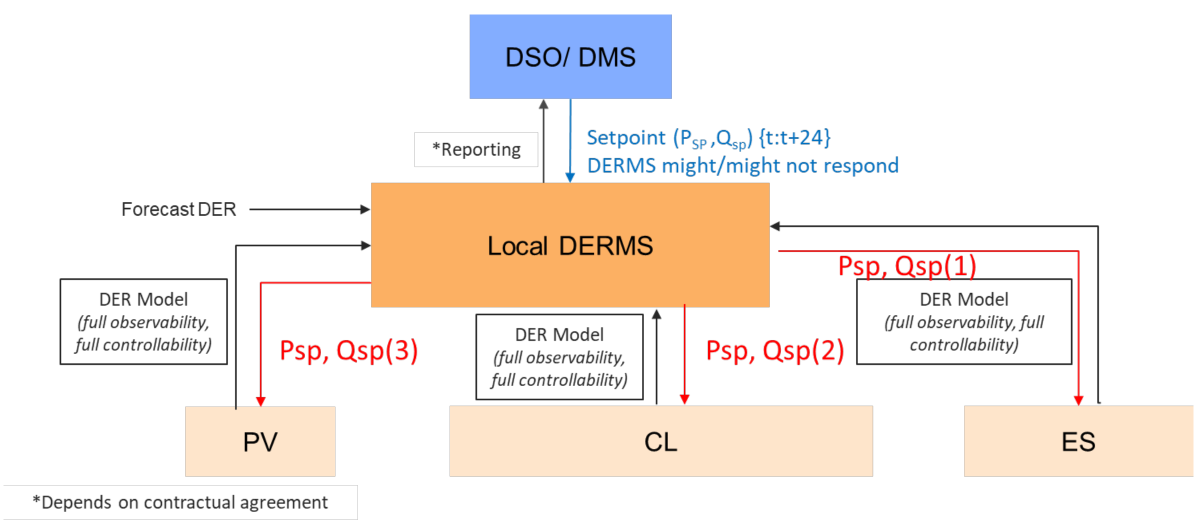

Figure 8. L-DERMS Providing a Service Without Booking, with Full Observability and Full Controllability Over the Resources it Manages

In Case C, shown in **Figure 9**, similar to Case A L-DERMS provides a service “with booking” to its managing entity. However, in Case C, L-DERMS does not have full controllability of the DERs it manages: instead of dispatching the DERs to their complete capability range, L-DERMS is limited to a certain range defined contractually.

Case C: L-DERMS providing a service “with booking”, and full observability and partial controllability of the resources it manages

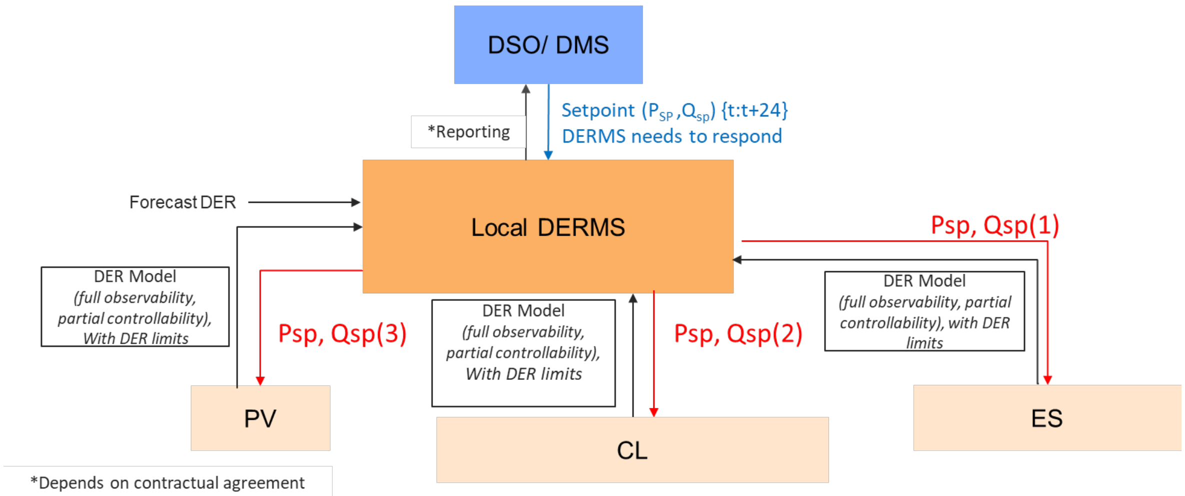

Figure 9. L-DERMS Providing a Service with Booking, with Full Observability and Partial Controllability Over the Resources it Manages

L-DERMS Objective

The objective of the DERMS remains the same as shown in Case A:

Minimize {Service deviation penalty + DER utilization cost + Retail electricity charges}

L-DERMS Constraints

Similar to Case A, the constraints that must be considered in the optimization problem are the DER constraints, the contractual constraints, and the service constraints (real and reactive). All constraints in Case C remain the same as defined in Case A, except for the DER constraints where additional contracts are included to reflect the partial controllability.

1. *DER constraints*: in Case C, the L-DERMS has partial controllability over the DERs, which is defined contractually as follows for each time interval:

$$DER_{min} \leq DER_{state} \leq DER_{max}$$

For example, a battery energy storage of size 1MW, 1hr may only be partially controllable, with the assumption that only 250kW is available for dispatch for a period of 1hr at any time of the day. For this example, the corresponding constraint is: $ES_i^t \leq 250 \; \forall \, t \in \{0,1, \dots .23\}$.

In Case D, shown in Figure 10, similar to Case B L-DERMS provides a service "without booking" to its managing entity. However, in Case D, L-DERMS has full observability, but partial controllability of the DERs it manages. Case D is further discussed in Appendix.

Case D: L-DERMS providing a service "without booking" and full observability, partial controllability of the resources

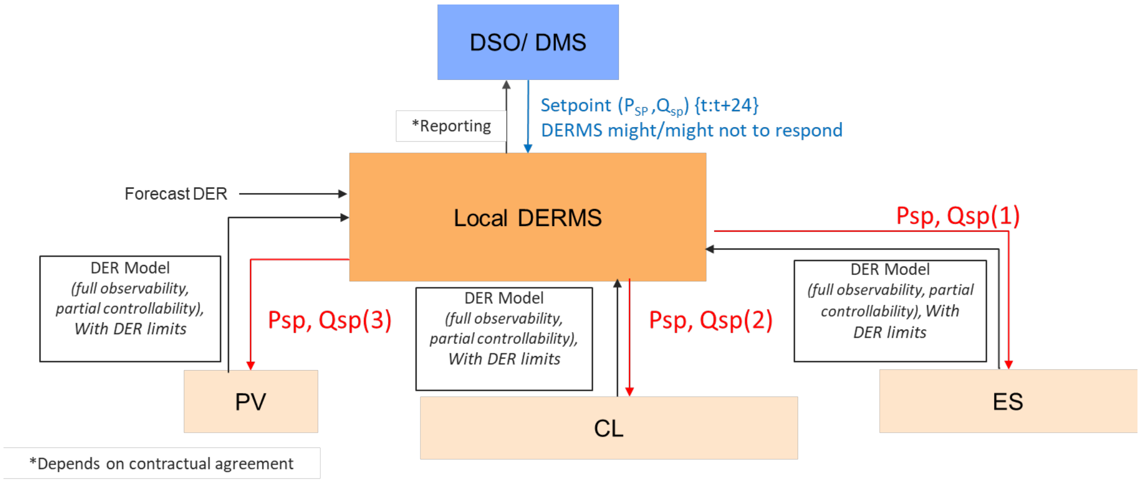

Figure 10. L-DERMS Providing a Service Without Booking, With Full Observability and Partial Controllability Over the Resources it Manages

The rest of this report focuses primarily on Cases A and C, where L-DERMS books capacity ahead of time to be prepared to respond to requests from its managing entity.

This chapter focused on the first layer of control where a local DERMS manages a group of DERs. In the next chapter, the control architecture is expanded to consider how multiple L-DERMS can be aggregated under a single A-DERMS, which itself communicates with a higher level managing entity, such as a DSO or ISO.

4
AGGREGATOR DERMS MANAGING A GROUP OF LOCAL DERMS

This chapter focusses on the second layer of control where an aggregator DERMS (A-DERMS) manages local DERMS (L-DERMS), and possibly standalone DERs.

Each A-DERMS manages a fleet of L-DERMS, or standalone DERs to respond to real and/or reactive power requests sent by a higher-level managing entity, such as an ISO or DSO. A-DERMS distributes the incoming service request across the resources it manages (L-DERMS or standalone DERs), taking into consideration the current capability or availability of each resource, and the contracted capability. In this report, it is assumed that each L-DERMS is paired with only one A-DERMS. But the same architecture could be extended for scenarios where multiple A-DERMS are communicating with the same L-DERMS.

Functionality of A-DERMS

A-DERMS communicates upstream with higher-level DER managing entities (e.g., DSO, ISO, etc.), and downstream with L-DERMS, and possibly other standalone DERs as shown in Figure 11. A-DERMS does *not* have full control or even visibility into the number, type, or capacity of DERs managed by each L-DERMS. Instead, A-DERMS uses a "simplified", "abstracted" model of the DER aggregation managed by each L-DERMS, which reflects the contractual agreement between A-DERMS and the corresponding L-DERMS.

For example, assume an L-DERMS is under a contractual agreement to deliver 50kW to the A-DERMS during any time of the day. The A-DERMS defines a simplified model of L-DERMS as follows: $P_{net}^{t} \leq 50 \; \forall \; t \in \{0,1, \dots 23\}$, where P_{net}^{t} is the total real power provided by the L-DERMS, which A-DERMS can request to be anywhere between 0 and 50kW. Yet, it is possible that the L-DERMS has a greater capability. For example, 100kW over a period of 24 hours. But this full range is not visible to the A-DERMS.

A-DERMS can act simultaneously as a managed entity and a managing entity: as a managed entity, A-DERMS offers services to a higher-level managing entity (e.g., DSO/ISO); as a managing entity, it coordinates its portfolio of resources downstream (i.e., one or more L-DERMS and possibly, one or more standalone DERs).

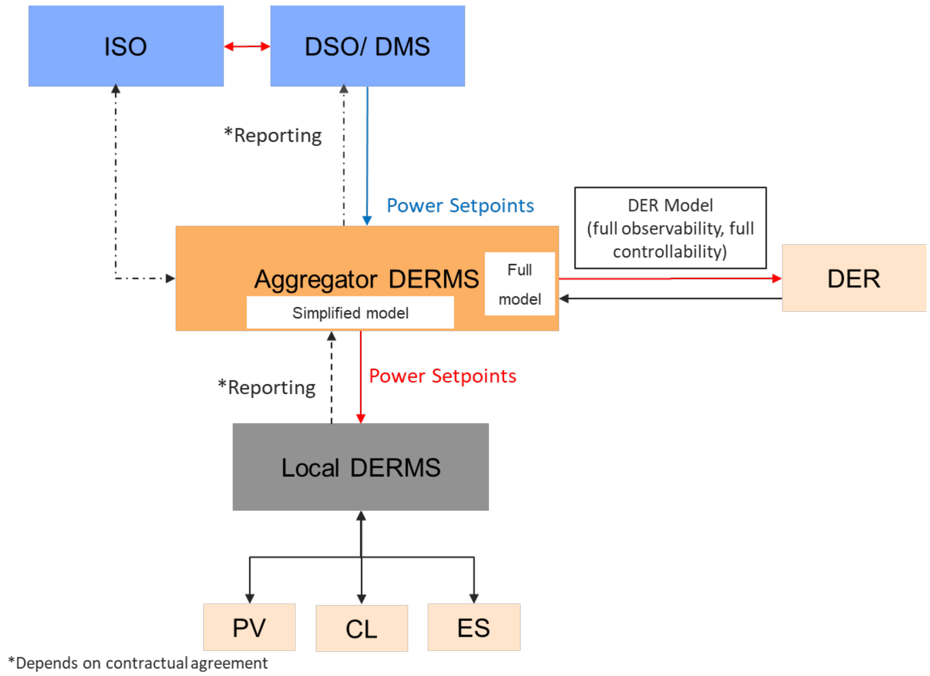

Figure 11. A-DERMS Interacting With One L-DERMS, and One Standalone DER

A-DERMS as a Managing Entity

The power availability and model constraints for each resource (e.g. standalone DER, L-DERMS) managed by an A-DERMS are dependent on the contractual agreement between these resources and the A-DERMS.

Figure 12 presents an example configuration where an A-DERMS provides capacity deferral service to the DSO. The A-DERMS manages two L-DERMS, and an energy storage (ES) system with full observability but partial controllability. The first L-DERMS ("LD1") manages a PV and an ES. The second L-DERMS ("LD2") manages a controllable load (CL) and an ES. This example configuration is used in the following to illustrate the role of A-DERMS as managing entity.

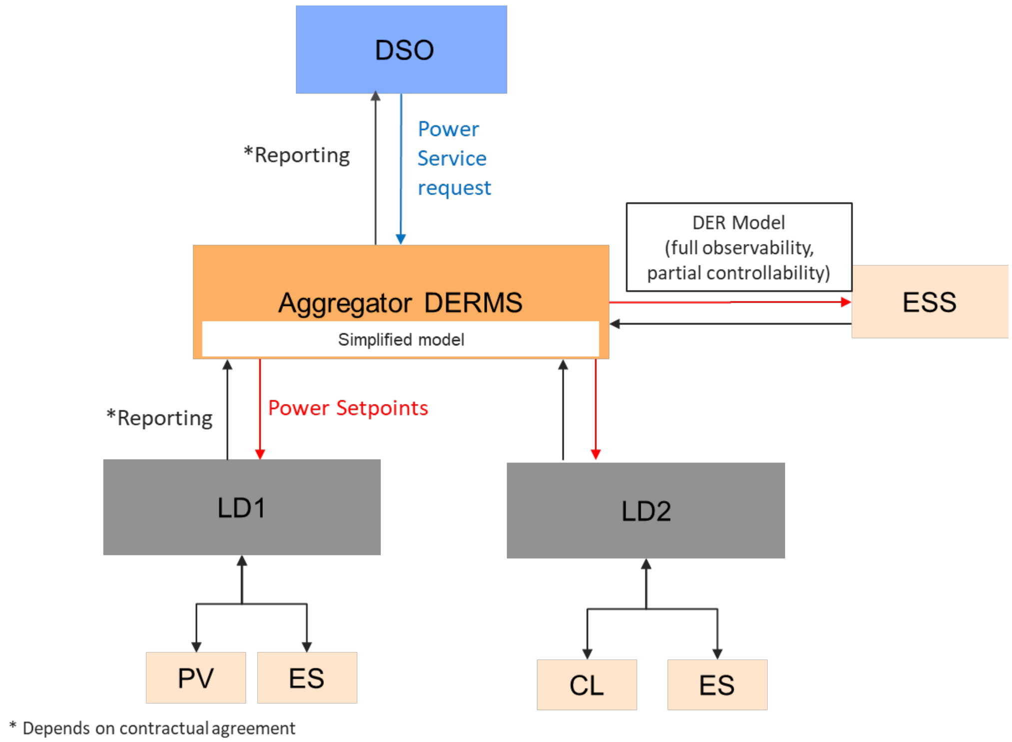

Figure 12. Example Scenario: A-DERMS Manages Two L-DERMS and a Standalone ESS

Consider a scenario where LD1 is under a contractual agreement with A-DERMS to provide 5kW during any time of the day except for 12:00 to 21:00, where it can provide 8kW. Similarly, LD2 has contractually agreed to provide 2kW during any time of the day except for 16:00 to 21:00, where it can provide 4kW. The standalone ESS is under contract to provide 3kW for a block of 3 contiguous hours, at any time of the day.

The contractual availability of LD1, LD2 and ESS is illustrated in Figure 13. Note that in this illustration, the availability of ESS is only shown between 18:00 to 21:00, but this 3-hour block can be moved to any time of the day.

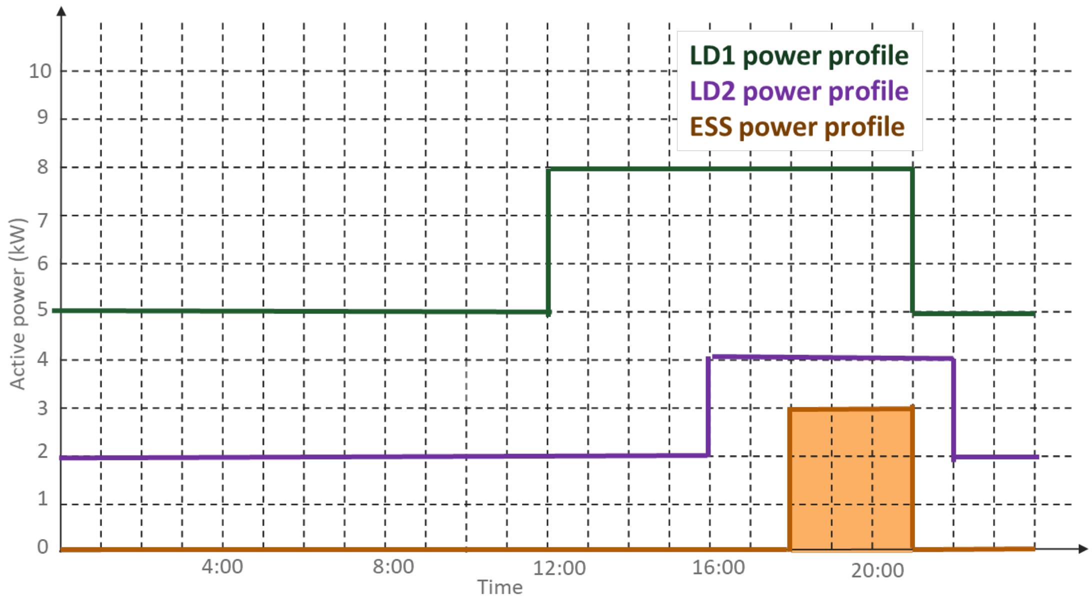

Figure 13. Contracted Availability of L-DERMS and DER with A-DERMS

As part of this illustrative scenario, it is assumed that the DSO sends an active power group dispatch command to the A-DERMS requesting a power dispatched between 18:00 to 21:00, as represented in Figure 14.

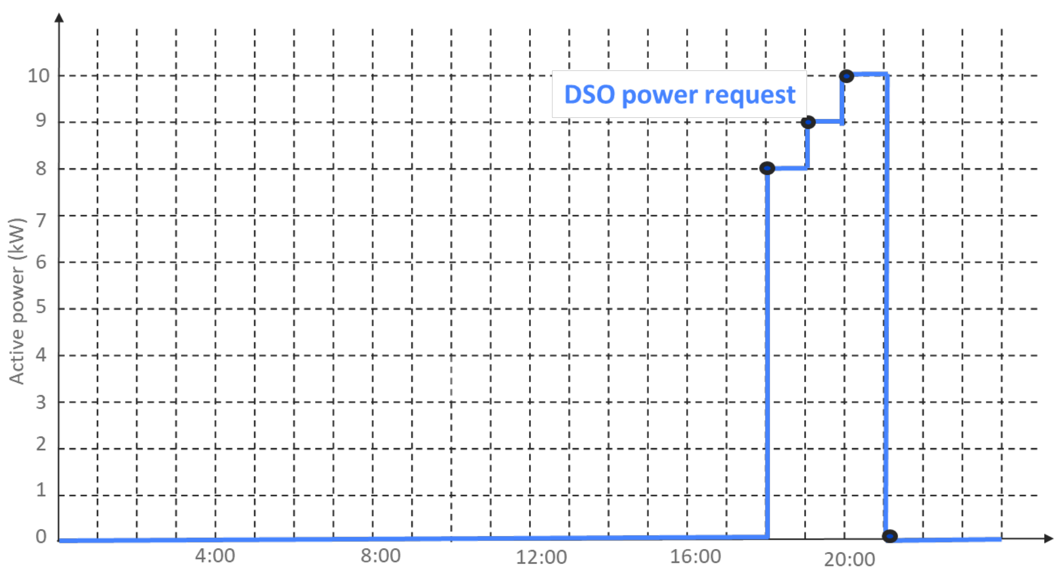

Figure 14. Active Power Group Dispatch Command from the DSO to A-DERMS

The rest of this section illustrates that there are multiple possible combinations of dispatch profiles the A-DERMS could select for LD1, LD2 and ESS to meet the DSO requirement. The final feasible set of profiles selected depends ultimately on the objective(s) pursued by the A-DERMS.

Three example sets of feasible dispatch profiles are discussed below for three different A-DERMS objectives:

Dispatch Example 1

A-DERMS objective: Dispatch resources to earn maximum profit using some economic dispatch algorithm[6].

Solution: Dispatch LD1 to its full capacity and then LD2 to deliver the rest as shown in Figure 15. The DSO request will be disaggregated by A-DERMS in the following manner:

a. LD1: 8kW from 18:00 to 21:00.
b. LD2: 1kW from 19:00 to 20:00, 2 kW from 20:00 to 21:00.
c. ESS: Not dispatched

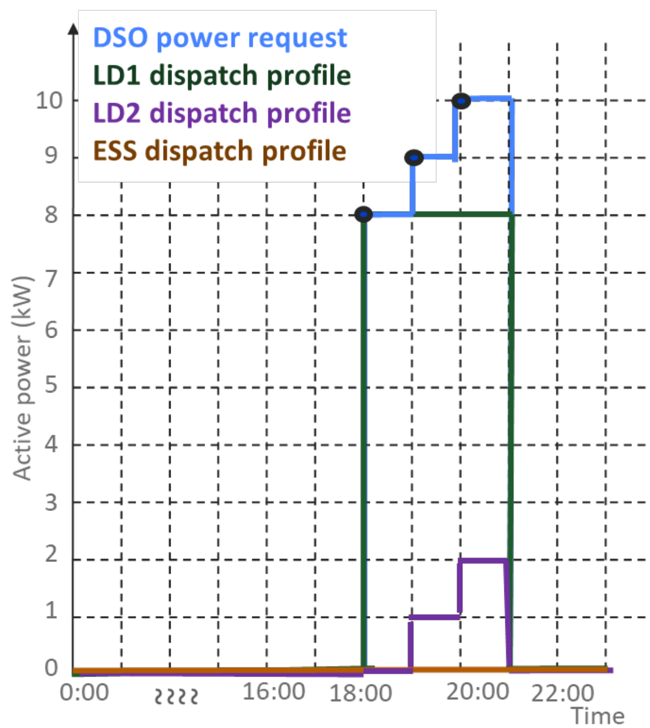

Figure 15. Individual Dispatch Commands from A-DERMS for Example 1

Dispatch Example 2

A-DERMS objective: Utilize all the resources equally
Solution: Dispatch all the resources uniformly as shown in Figure 16. The DSO request will be disaggregated by A-DERMS in the following manner:

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[6] This algorithm could be a cost-based, optimization algorithm or some other rule-based algorithm that provides maximum profit to A-DERMS. The logic applied in this report is explained under the control logic section of the chapter.

a. LD1: 2.33, 3, 3.5 kW at 18:00, 19:00, 20:00 respectively
b. LD2: Similar dispatch commands as LD1
c. ESS: 2.33, 3, 3kW kW at 18:00, 19:00, 20:00 respectively

Since ESS output is capped at 3kW at t=20:00 LD1 and LD2 provide an equal amount of the remainder of DSO power service request of 7kW.

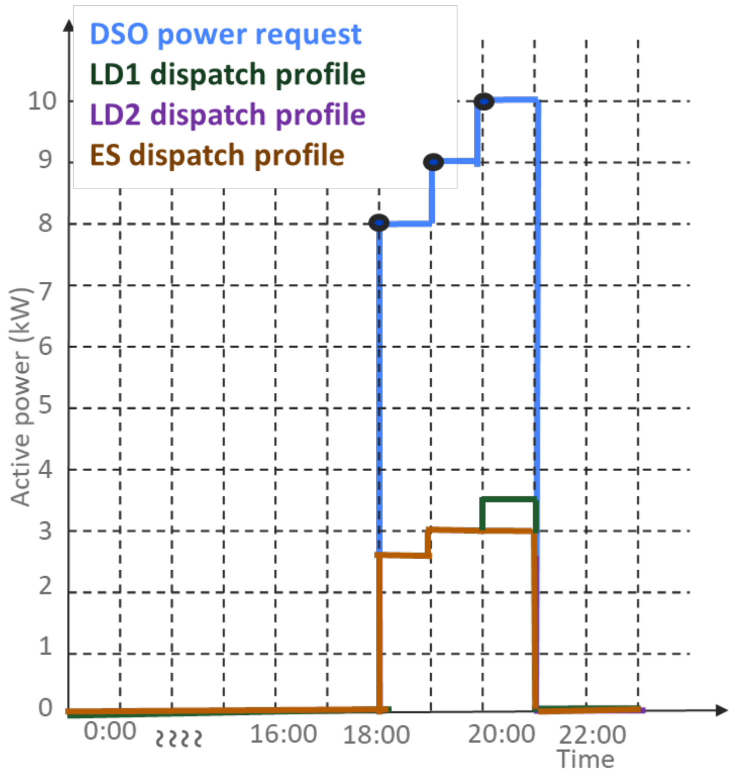

Figure 16. Individual Dispatch Commands from A-DERMS for Example 2

Dispatch Example 3

<u>A-DERMS objective</u>: Utilize ESS to its maximum capacity and remaining from LD1 and then LD 2.

<u>Solution</u>: Here, the DSO request will be disaggregated by A-DERMS in the following manner:

a. LD1: 5kW from 18:00 to 19:00, 6kW from 19:00 to 20:00, 7 kW from 20:00 to 21:00
b. LD2: Not dispatched
c. ESS: 3kW from 18:00 to 21:00

Figure 17 shows the individual dispatch commands for all the resources.

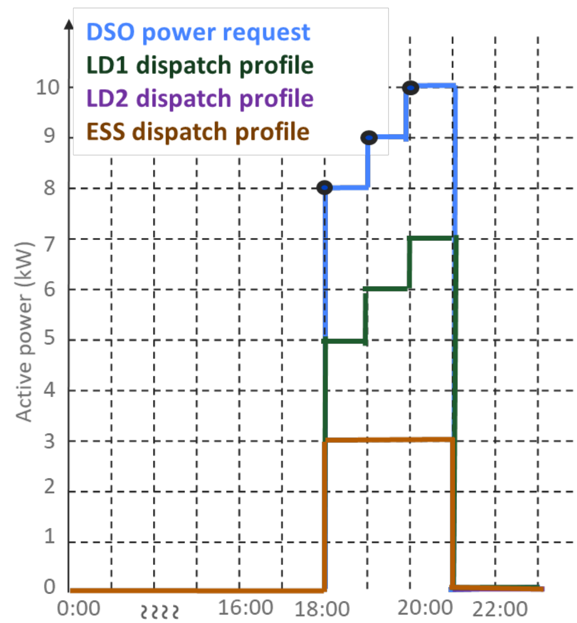

Figure 17. Individual Dispatch Commands from A-DERMS for Example 3

The three dispatch examples above only show three resources (two L-DERMS and one ESS) being managed by an A-DERMS, for illustrative purposes. Naturally, real-world scenarios may involve a greater number of resources managed by an A-DERMS. As the number of resources increases, the feasible combinations of dispatch profiles also increase. Thus, A-DERMS needs a control logic or disaggregation method to select a feasible solution based on the A-DERMS objectives. This is explained further in the following sections.

A-DERMS as a Managed Entity

A-DERMS acts as a managed entity when it receives, and subsequently responds to service requests from upstream managing entities (i.e., ISO/DSO). When acting as a managed entity, A-DERMS dispatches the resources it manages according to the service request(s) it receives from the managing entity. Depending on the contractual agreement between A-DERMS and the managing entity, A-DERMS may be required to respond, or may *choose* to respond to the service request. In this report, these two arrangements are respectively referred to as "with booking" and "without booking".

This report focuses primarily on the "with booking" arrangement, where A-DERMS agrees contractually to reserve capacity and provide one or several grid services when called by the managing entity during agreed upon time intervals. The service requests sent by the managing entity must be in line with the contractual agreement. Depending on the contract, A-DERMS might incur penalties or may be removed from service if unable to deliver as expected. For this reason, A-DERMS needs to ensure that sufficient capacity is reserved, even if some of this capacity may not always be fully used.

When providing a service "with booking", A-DERMS can be called upon to effectively perform a service in two ways:

1. *Pre-planned service requests*: Ahead of the period of performance, the managing entity sends a service request to A-DERMS (for example, the day before). Depending on the service, this request may take the form of a requested power profile. A-DERMS has time to prepare its response and starts to effectively deliver the service when the period of performance begins. Once service delivery has started, the managing entity still has the option to request adjustments if the system conditions change.
2. *Instantaneous service requests*: The managing entity sends the request to activate the service to A-DERMS *after* the period of performance has started. A-DERMS is expected to be ready with the available capacity reserved and respond in short order following receipt of the service activation request.

Illustrative examples for both *Pre-planned service requests* and *Instantaneous service requests* scenarios are provided below. For simplicity, it is assumed in these examples that the service request takes the form of a power profile that A-DERMS has to provide. This could correspond to a distribution capacity service contracted by the DSO.

Pre-planned service requests

In this first illustrative example, represented in Figure 18, the managing entity sends a service activation request to A-DERMS with a lead time of 2 hours. The power profile characterizing the service request spans a forward-looking time horizon of 25 hours, labeled H1 to H25.

At t_1 (22:00 on previous day), the managing entity sends a service activation request, instructing A-DERMS to provide 3MW from H1 to H12, 3MW from H21 to H24, and 6MW from H12 to H21. This request is represented by the light blue trace on Figure 18. In response, A-DERMS starts dispatching 3MW at 0:00.

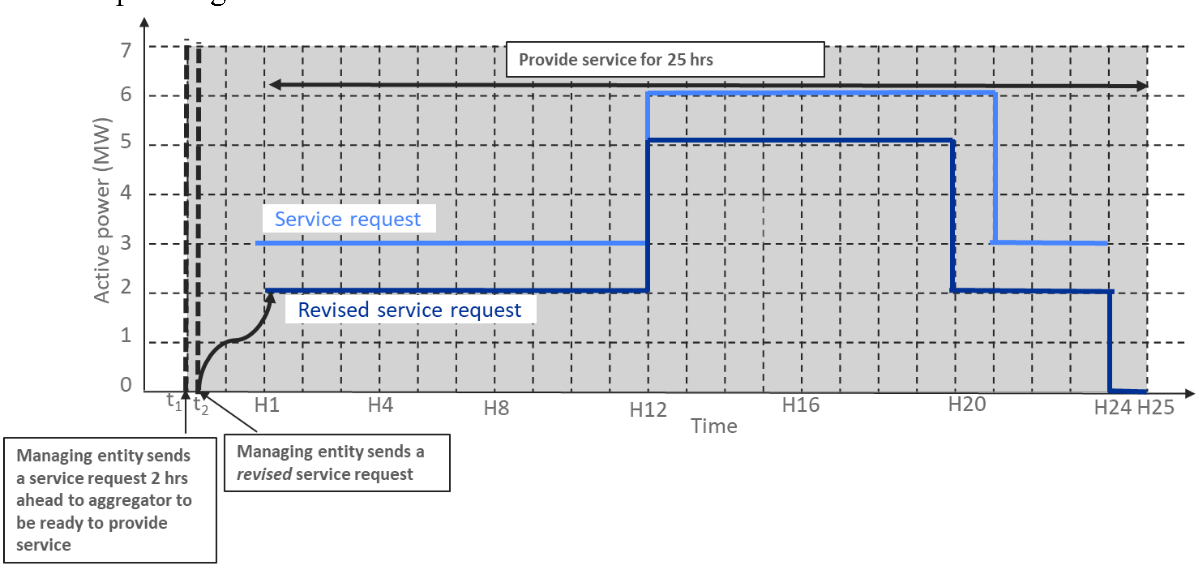

Figure 18. Managing Entity Planned Service Request

Yet, at t_2 = 00:15, the managing entity provides a *revised* request that supersedes the original request. System conditions have evolved, and as a result the service request is modified to 2MW from H1 to H12, 2MW from H20 to H24, 5MW from H12 to H20, and 0MW at H25. This updated required is presented by the deep blue trace on Figure 18. In response to the revised request, A-DERMS decreases its dispatch down to 2MW at the top of the next hour, and revises its planning accordingly for the next few hours.

Instantaneous service requests

In this second illustrative example, the period of performance also started at 00:00. However, no advance notice on the actual power profile requested was received ahead of the period of performance. Instead, the DSO, acting in this example as managing entity, informs A-DERMS at 04:00 that it should start performing at 08:00, and until 17:00.

At 11:00, if first request is received to provide 10kW, followed by a second request at 12:00 (increase to 20kW), and a third request at 13:00 (increase to 30kW). At 14:00, a request to terminate service delivery is sent.

Table 3 shows the contractual commitment of A-DERMS. As expected, the successive activation requests sent by the DSO, and illustrated in Figure 19, are compatible with the contractual agreement between the DSO and A-DERMS. Figure 20 shows A-DERMS response to the DSO requests, and the remaining capacity available per contract.

Table 3. A-DERMS Contractual Commitment

Commitment condition	Capacity (kW)	Delivery Hours	Hours Duration
I.	30	8:00 AM– 1:00PM	2
II.	50	1:00 PM- 4:00PM	1

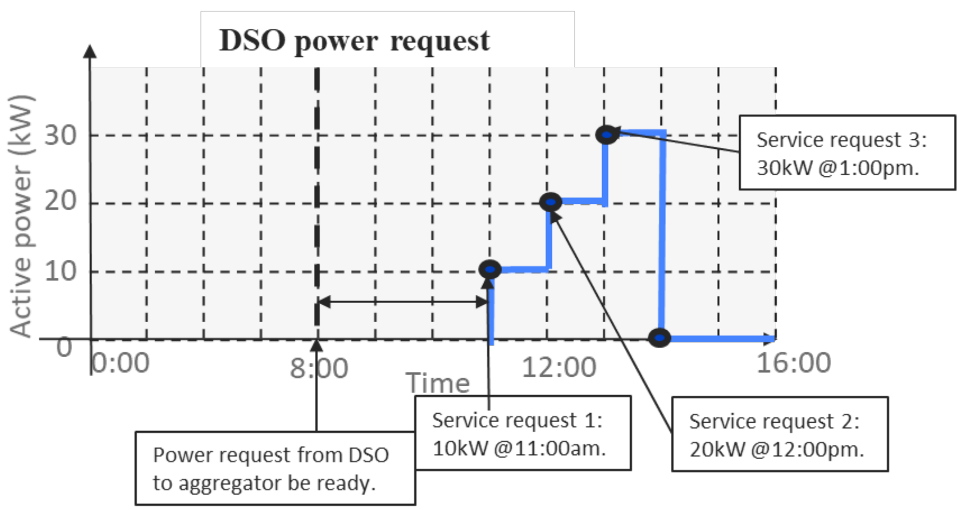

Figure 19 DSO Service Request to A-DERMS

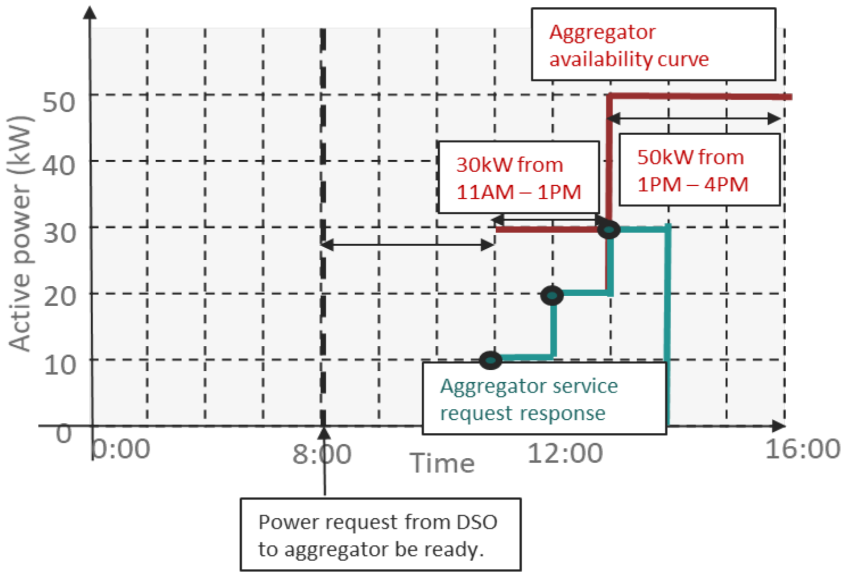

Figure 20. A-DERMS Availability and Service Response

In this illustrative example, A-DERMS had reserved sufficient capacity and was able to successfully meet its contractual commitments, as shown in Figure 20. However, some of the capacity contractually booked was unused.

A-DERMS response to high-frequency requests

Some grid services, such as frequency regulation, may require a rapid and frequent response to control signals from the managing entity (e.g., adjustments every 4 seconds). When such rapid response is required, it is likely that A-DERMS must pre-assign one or several of the resources it manages to respond: a first planning stage consists of determining which resource(s) are most adequate to provide the service; once assign, these resource(s) are responsible to response. Indeed, re-solving a dispatch problem to determine which resource(s) should respond every few seconds would likely be impractical. In addition, going through multiple control layers every few seconds (i.e., optimization at the A-DERMS layer, optimization at the L-DERMS layer) would likely involve computational and communication delays exceeding the time by which a response is required. The delays would grow as the number of L-DERMS, and number of resources managed by L-DERMS grow. For grid services that do not require a rapid response time (e.g., capacity deferral), these time delays may be acceptable, and A- DERMS may choose to solve an optimization problem every time a new request is received.

Control logic of A-DERMS

The sections above illustrated the need for A-DERMS to be equipped with some control logic that can select a “best” feasible solution that meets all constraints, including service requirements, and maximizes the A-DERMS objectives. This section defines an optimization-based control logic that allocates the grid service request to each resource managed by A-DERMS.

Sequence of Operation

When a service activation request is received by A-DERMS, it first checks the status of each of its resource (L-DERMS/standalone DER). Once their availability is confirmed, the control logic selects a feasible solution, and dispatch requests are sent to all the resources managed by A-DERMS. Figure 21 shows the section of actions. L-DERMS utilizes the dispatch requests received from A-DERMS, and schedules the resources it manages (e.g., storage, controllable loads, etc.) to satisfy the request.

A-DERMS regularly checks that the resources it manages (L-DERMS/standalone DER) continue to be available and responsive. If a resource becomes only partially available, or simply unavailable, the A-DERMS control logic re-solves the problem, and re-dispatch control signals across the resources that remain available as needed.

The sampling rate at which the A-DERMS checks the continued availability of the resources it manages and recomputes the control problem is a tuning parameter which depends on the reliability level at which L-DERMS is expected to deliver on its contractual commitments.

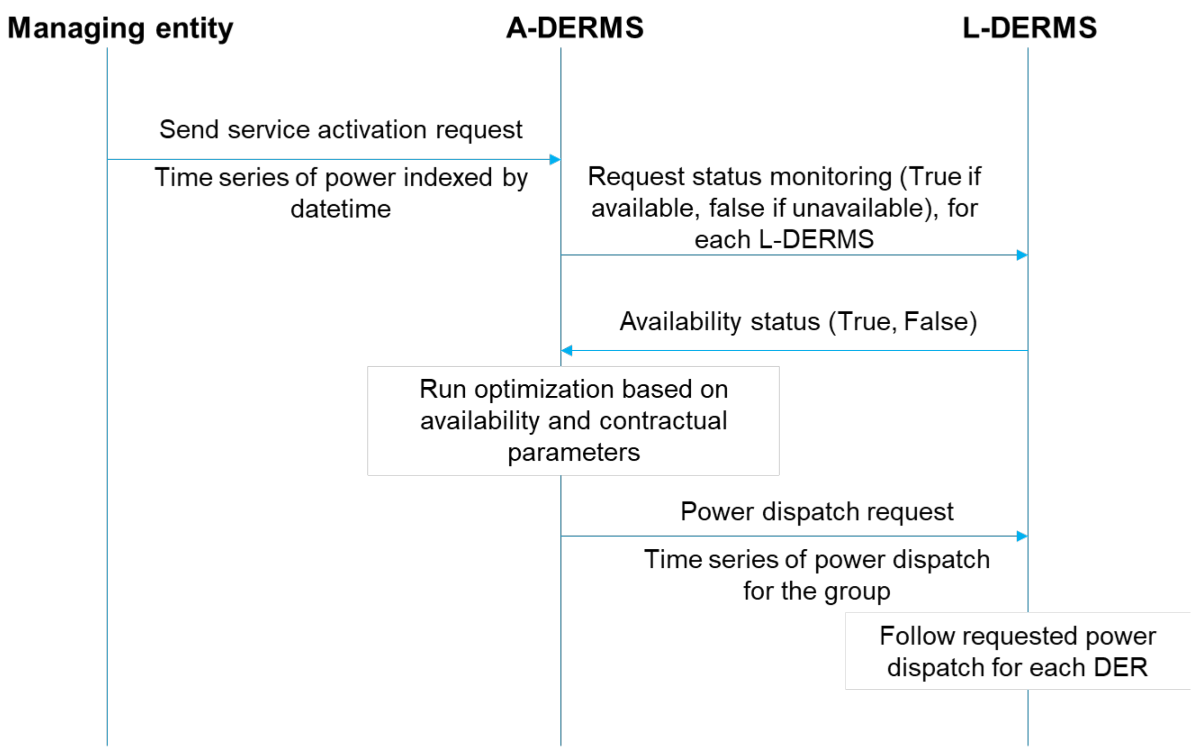

Figure 21. Sequence of Operation of A-DERMS

Problem Formulation

Let G be the group of resources (L-DERMS/standalone DER) managed by A-DERMS that responded positively to the status check request. Let E_i be the set of rows from the resource capacity delivery from each L-DERMS. Let $\tau=\{1,\ldots,T\}$ be the set of time periods that cover the service performance period. Let c_t be the capacity requirement received from the higher-level managing entity for each $t \in \tau$.

A-DERMS solves an optimization problem to dispatch each of its resources. The objective and constraint of the problem are explained next.

A-DERMS Objective:

$$minimize \sum_{i \in G} \eta_i \sum_{t \in \tau} p_t^i$$

The objective corresponds to the total cost of addressing the requirement received from the higher-level managing entity, given the cost of using each A-DERMS resources is η_i where i is the group of resources (G). The optimization variables are $x_t^{i,j}$, $\alpha_t^{i,j}$ and p_t^i, where p_t^i is the total power of capacity delivered from resource i at time t for all $i \in G,\ t \in \tau, j \in E_i$.

A-DERMS Constraints:

1. Total power constraint: The total power available from each resource is equal to the power associated with each one of the capacity rows. The constraint is defined as:
   $$p_t^i = \sum_{j \in E_i} x_t^{i,j}, \text{ for all } i \in G,\ t \in \tau, j \in E_i.$$
2. Resource limit constraint: Each resource has a limited amount of power and energy capacity defined contractually. The power and energy limit constraints are defined below.
   a. Power limit
      $0 \leq \alpha_t^{i,j} * x_t^{i,j} \leq \mathrm{Power_j}$, for all $i \in G,\ t \in \tau, j \in E_i$
   b. Duration limit
      $\sum_{t \in \tau} \alpha_t^{i,j} = Duration_j$, for all $i \in G,\ t \in \tau, j \in E_i$,
      $\alpha_t^{i,j} \in \{0,1\}$
3. Service request constraint: The total power available from all the resources must be greater or equal than the requirement (c_t) received from the higher-level managing entity. This constrained is modeled as:
   $$\sum_i p_t^i \geq c_t, \text{ for all } t \in \tau$$

The above optimization problem is solved to evaluate the dispatch setpoints sent to each of the resources managed by A-DERMS.

5 MESSAGING AND COMMUNICATION PROTOCOLS

This chapter focuses on the communication requirements between the control architecture components presented in Figure 1.

A standard set of messages exchanged between each control architecture component must be defined to integrate multiple levels of controls. These communication requirements may vary according to the level of control, type of component and, grid service considered. This section explains in detail the communication requirements needed to seamlessly integrate these systems.

The managed and managing entity communicate via the following two types of messages, depending upon hierarchical proximity to the DER:

- *Group messages* – Messages exchanged between entities that typically manage a group of devices, and do not manage DER directly. Examples include the messages between the following:
  - ISO/DSO and A-DERMS
  - A-DERMS and L-DERMS
- *Device-level messages* – Messages exchanged between DER (such as one or more ES and PV units) and their managing entity (L-DERMS, or possibly A-DERMS for standalone DERs).

The rest of this chapter focuses on message types and communication protocols.

Group messages

Two DER-group (DERG) level functions need to be exchanged between the control architecture components to enable grid service delivery. These are defined as follows:

DERG.1 Status monitoring requests and responses: This function provides information on the present status of the managed entity. *Status* here refers to the present value and range of available adjustable power levels of the managed entity.

DERG.2 Grid service request and responses: This function provides details on the amount of power service requested or dispatched from a managed entity.

Group messages are classified into two types, depending on their direction:

- Group requests, flowing from managing entity to managed entity;
- Group responses, flowing from managed entity to managing entity.

Each message comprises of multiple information fields where each field defines a particular information of the message. For example, if the managing entity is sharing its ID to a managed entity, then the message would be [Requesting Entity ID, Managed Entity ID][7,8]. Entities might exchange only some of the message information according to their role and placement in the

[7] Common functions for DER Group Management report, EPRI, November 2016: 3002008215

[8] DER Group Management for Coordinated Operations Across the T&D Interface, EPRI, December 2020: 3002016174

control architecture. These are explained in detail for each type of DERG functions (DERG.1 or DERG.2) in Table 4.

Table 4. Message Information Details

Information Name	*Description*	*DERG Function*	*Group requests*	*Group responses*
Action Identifier	Defining what is being requested: • DER Group status request • Absolute Real Power Level • Real power dispatch request response *As specified in: DER group Status monitoring*[7], *DER group Real power dispatch*[8]	Monitoring/ Grid service	✓	✓
Managing Entity ID	Defined as *requesting entity ID*[7,8]	Monitoring/ Grid service	✓	✓
Managed Entity ID	This ID can refer to an A-DERMS, L-DERMS or a DER as well. Defined as *DER group ID*[7,8].	Monitoring/ Grid service	✓	✓
Timing of Status Request	Defining whether the request is for: • Latest Available • Refreshed Status *As specified in: DER group Status monitoring*[7]	Monitoring	✓	
Power Quantity ID	Identifier of which power parameter is being dispatched/requested: Power Total (Delivered or Received) / Power Phase A/B/C (Delivered or Received) *As specified in Real Power (Energy) Dispatch*[8]	Monitoring/ Grid service	✓	✓
Managed entity status responses	Information related to present state that may be exchanged in group status responses[7]	Monitoring		✓
Schedule Array	An array of N schedule points of power service request can be defined in two formats. These formats are explained in detail in Appendix C.	Grid service	✓	
Schedule Ramp Time	An optionally specified time window (in seconds) over which the group real power is to be adjusted in response to this control action. When included, this is the time it takes for the resource to respond to within 90% of its ultimate value[8]	Grid service	✓	

Success / Failure Indicator(s)	*As specified in Real Power (Energy) Dispatch*[8]	Monitoring/ Grid service		✓

The information model for each DERG function (1,2) is available under *DERGroupStatuses* and *DERGroupDispatches* profiles respectively in IEC 61968-5[9]. The information fields defined above might be needed at a varying frequency rate for each DERG function. These are explained further below.

DERG Function: Status monitoring

The frequency of status messages exchanged depends on the type of grid service enabled, DER resources, contractual agreement, and geographical location of the resources. A combination of these factors impacts the timing of status monitoring messages. Status monitoring responses are required whenever a status monitoring request is sent by the upstream managing entity.
The status monitoring requests sent from the managing entity are explained further in Table 5.

Table 5. Status Monitoring Requests Sent from Managing Entity to Managed Entity

Information Name	*Description*
Action Identifier	Defining what is being requested: • DER Group status request
Managing Entity ID	*As defined in* Table 4
Managed Entity ID	*As defined in* Table 4
Timing of Status Request	Defining whether the request is for: • Latest Available • Refreshed Status
Power Quantity ID	Identifier of which power parameter is being requested. *Defined in detail in* Table 4

A sample status monitoring request message would be: [DER Group status request, MRID 1, MRID 2, NA, Latest Available, Total Power delivered, NA, NA, NA, NA]

The status monitoring responses sent from the managed entity are explained further in Table 6.

[9] Available [Online] https://webstore.iec.ch/publication/60069

Table 6. Status Monitoring Responses Sent from A-DERMS to ISO/DSO or L-DERMS to A-DERMS

Information Name	*Description*
Action Identifier	Defining what is being dispatched: • DER Group status request
Managing Entity ID‡	*As defined in* Table 4
Managed Entity ID	*As defined in* Table 4
Power Quantity ID	Identifier of which power parameter is being requested. *Defined in detail in* Table 4
Managed entity status responses	*As defined in* Table 4
Success / Failure Indicator(s)	*As defined in* Table 4

A sample status monitoring response message would be: [DER Group status request, MRID 1, MRID 2, 1, NA, Total Power delivered, Status responses[2], NA, NA, Success[2]]

DERG Function: Grid service

This message can be received ahead of time or in real-time, the frequency of power service messages is dependent on the type of service, managing entity and contractual agreement.

The grid service requests sent from the managing entity are explained further in Table 16.

Table 7. Grid Service Requests from Managing Entity to Managed Entity

Information Name	*Description*
Action Identifier	Defining what is being requested: • Absolute Power Level • Power Adjustment
Managing Entity ID	*As defined in* Table 4
Managed Entity ID	*As defined in* Table 4
Power Quantity ID	Identifier of which power parameter is being requested. *Defined in detail in* Table 4
Schedule Array	*As defined in* Table 4
Schedule Ramp Time	*As defined in* Table 4

A sample power service request message would be: [DER Group status request, MRID 1, MRID 2, NA, NA, Total Power delivered, NA, Schedule array [t1, deltaT1, settings values], Ramp schedule[2], NA]

The power service responses sent from the managed entity are explained further in Table 8.

Table 8. Grid Service Responses from Managed Entity to Managing Entity

Information Name	*Description*
Action Identifier	Defining what is being requested: • Power dispatch request response
Managing Entity ID	*As defined in* Table 4
Managed Entity ID	*As defined in* Table 4
Power Quantity ID	Identifier of which power parameter is being requested. *Defined in detail in* Table 4
Success / Failure Indicator(s)	*As defined in* Table 4

A sample power service response message would be: [DER Group status request, MRID 1, MRID 2, NA, NA, Total Power delivered, NA, NA, NA, Success]

Device-level messages

Device level messages are exchanged between L-DERMS and the DER devices. L-DERMS can send power service request and extract DER status information in order to provide service to its managing entity.

L-DERMS acts a managing entity for each DER and sends a DER set point according to the type of DER. These setpoint values are just one value (not a schedule of multiple points) that the DER needs to implement. For example, if L-DERMS sends charge setpoint to ES, it needs to start charging according to that rate. Similarly, DER acting as a managed entity needs to respond the service, status requests as required from L-DERMS. This project leverages the messaging architecture defined in EPRI SHINES project for communication between DERMS and DER[10,11].
The power service request and responses exchanged between a managing entity and managed DER are explained further in Table 9 and Table 10.

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[10] *EPRI SHINES: Beneficial Integration of Solar PV, Energy Storage, Load Management, and Solar Forecasting: Conceptual Design, Functional Requirements, and Performance Metrics for the Control Architecture and Components*. EPRI, Palo Alto, CA: 2021: 3002010285

[11] *EPRI SHINES Solution: Beneficial Integration of Solar PV, Energy Storage, Load Management, and Solar Forecasting*. EPRI, Palo Alto, CA: 2021: 3002022464

Table 9. Power Service Requests from L-DERMS (or similar) Managing Entity to Managed DER

DER Type	*Information Name*	*Description*
PV, ES	Action Identifier	Defining what is being requested: • Absolute power level • Power adjustment
Water heater, thermostat, pool pump, etc.	Action Identifier	Defining what is being requested: • Operation mode adjustment • Operating speed • Setpoint
Any/all	Parameter Argument	Desired power value, mode, setpoint, etc. to be sent
Capable DER	Start time	Expected time (absolute or relative) when plans to start acting on command value

Table 10 Power Service Responses from Managed DER to Managing Entity (L-DERMS/A-DERMS)

DER Type	*Information Name*	*Description*
All DER	Managed Entity ID	Defined as *DER MRID,* if it has one
All DER	Current status/ operating mode	Defining what is currently running • Operation mode • Setpoint • On/off/running/not-running status
All DER	Commanded mode	Last received commanded mode/state from managing entity
All DER	Commanded value	Last received commanded parameter argument from managing entity
ES, pool pump, water heater, thermostat	DER state	State of the DER such as: • State of charge • Estimated energy take capability • Estimated energy stored • Temperature(s)
PV, ES, other DG	Delay	Parameter expressing desired delay from time of receipt before acting on command (likely 0)

Communication Protocols

The communication protocols used typically differs between group and device level message types. Group messages are often shared via standard communication protocols such as:

OpenADR, IEEE 2030.5, while DER level messages are typically communicated using protocols such as: DNP3, Modbus, IEEE 2030.5, CTA-2045, and OpenADR.

At present, there is no standard protocol used between different entities, and what has been used historically typically depends on the type of device/controller and the expected use cases. When it comes to DER, battery energy storage systems (BESSs) might use DNP3, while PV are typically set up for SunSpec Modbus. The specific protocol usually aligns with capabilities of the device, so SunSpec Modbus for example, has provisions for advanced inverter function parameters that PV systems might employ. In contrast, communication with DER such as water heaters or thermostats has evolved from demand response programs and thus uses more directional commands such as ‘load up’ and ‘shed’ from protocols like CTA-2045 and Open-ADR. In order to be able to talk to different DER types, L-DERMS will need to be capable of supporting multiple protocols and translating between them.

6
APPENDIX A: ADDITIONAL ARCHITECTURAL CASE

Case B: L-DERMS providing a service “without booking”, and full observability and controllability of the resources it manages

In Case B, shown in Figure 22, L- DERMS has full observability and controllability of the DERs it manages. L-DERMS provides a service “without booking” to its managing entity, i.e. L-DERMS does not commit to reserve capacity and respond to requests from the managing entity. However, the managing entity may still send a request; then, L-DERMS has the option to respond (or not) depending on its present resource availability and other local objectives. If L-DERMS chooses to respond, it then commits to deliver.

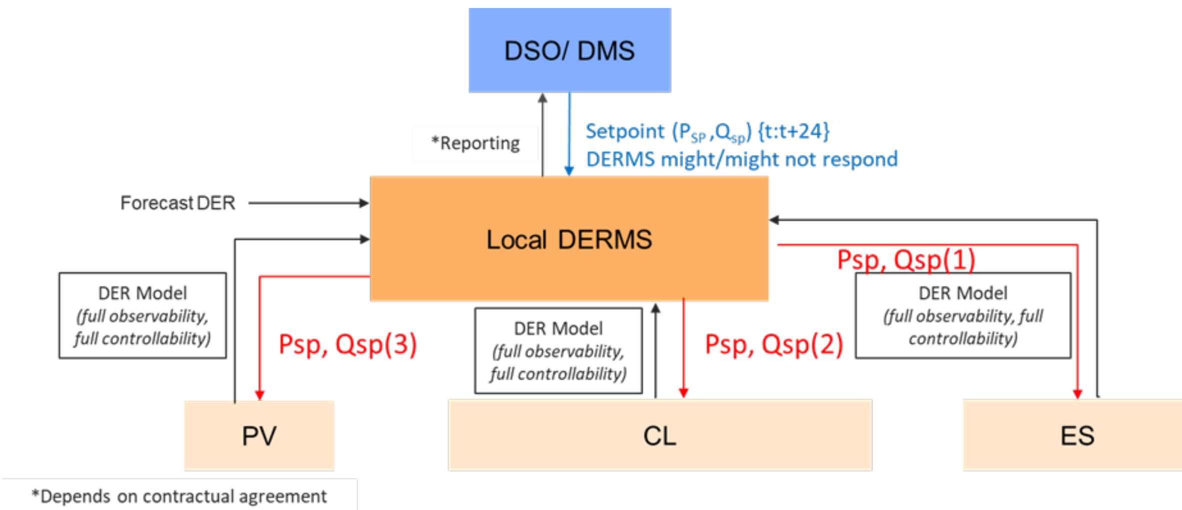

Figure 22. L-DERMS Providing a Service Without Booking, with Full Observability and Full Controllability Over the Resources it Manages

L-DERMS Objective

$$\text{Minimize}\ \ \{\text{DER utilization cost} + \text{Retail electricity charges} - \text{Service payment}\}$$

The elements constituting the L-DERMS objective function are each defined as follows:

The formulation for *DER utilization cost* and *Retail electricity charges* is similar to what was defined in Case A. Further, and different from Case A, no *Service deviation penalty* is considered in Case B since no booking is involved: the L-DERMS can decide to respond or not to the grid service opportunity on the spot.

Service payment is a new element of the objective function specific to Case B, which reflects that the potential revenues from the service opportunity are considered to determine if participation is beneficial, and to what extent:

- The *Service payment* component models the payment received by A-DERMS for providing the service.

The Service deviation penalty is defined as: $A * (total\ grid\ service\ provided)$

The coefficient $\boldsymbol{A}$ is associated with the service payment and reflects the proposed financial compensation for performing the service.

L-DERMS Constraints
The mathematical formulation developed considers two types of constraints in the optimization problem solved by the L-DERMS: DER constraints, and Service constraints (on real and/or reactive power).

1. *DER constraints*: same as in Case A.

2. *Service constraint*: Each service request is modeled as a soft constraint, where the total power dispatched can be less than or equal to the active power setpoints sent by the managing entity. This reflects the fact that the customer is free to respond to the service opportunity up to a certain limit, but could also decline to participate:
    - The real power constraint is formulated as:
      $\sum_{i=0}^{i=number\ of\ DER} P_i - P_{baseline} \leq Psp$
    - Reactive power setpoints–
        - If all DER managed by the L-DERMS provide reactive power support, the constraint is formulated as:
          $\sum_{i=0}^{i=number\ of\ DER} Q_i \leq Qsp$
        - If only one DER is predefined to provide reactive power support, the constraint is modeled as:
          $Q_{\mathrm{i}} \leq Q_{sp}$ where DER i is assigned to provide reactive power support

The MPC approach and the fast feedback control are same as described in Case A.

Case D: L-DERMS providing a service "without booking", and full observability and partial controllability of the resources it manages

In Case D, shown in Figure 23, the L-DERMS has full observability but partial controllability of the DERs it manages. Further, L-DERMS provides a service "without booking" to its managing entity, i.e. L-DERMS does not commit to reserve capacity and respond to requests from the managing entity.

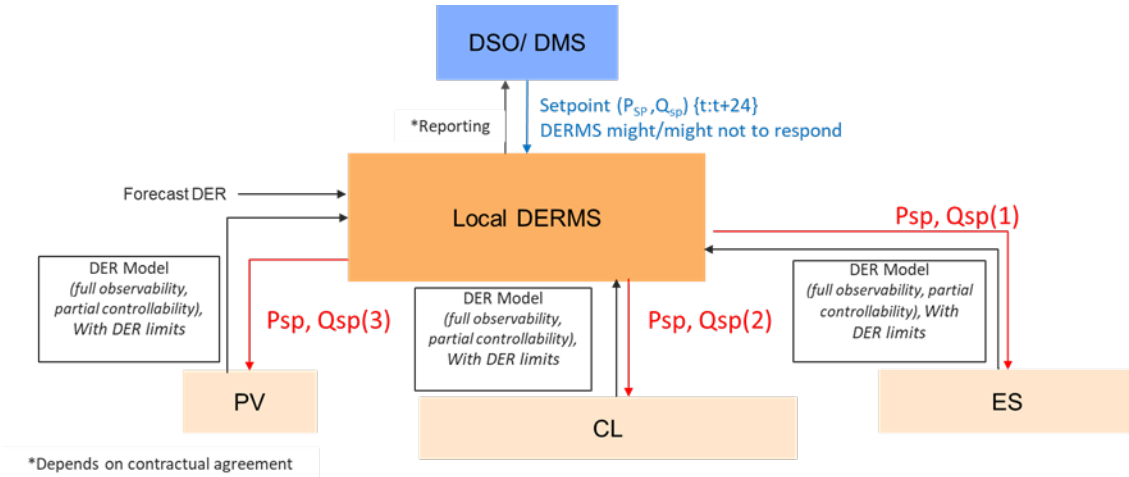

Figure 23. L-DERMS Providing a Service Without Booking, With Full Observability and Partial Controllability Over the Resources it Manages

Case D can be considered as a partial mixture of Cases B and C. As explained earlier in Case C, since the L-DERMS has partial controllability over the resources it manages, there will be limited amount of power that will be available for local DERMS to control and set.

L-DERMS Objective: As defined in Case B.

L-DERMS Constraints
Service (real and reactive) constraint, DER constraint (with partial controllability)

- Service (real and reactive) constraint: Net power requested may be equal or less than the net power delivered. These are modeled in the same fashion as shown in Case B.
- DER constraint: Since the DER are partially controllable, DERMS partially control the DER to vary its state within a limit set for the DER. Similar to Case C, these are defined as:

$$DER_{min} \leq DER_{state} \leq DER_{max}$$

7

APPENDIX B: FUNCTIONAL REQUIREMENTS FOR LOCAL DER DEVICES

DER Devices Considered

This project considers that L-DERMS can manage any combination of the DERs listed in Table 11.

Table 11. DER Devices Considered

DER resource	Control Variables
PV system	P (generation), Q (inject or absorb)
Energy storage	P (charge or discharge), Q (inject or absorb)
HVAC system	Temperature deviation from original setpoint
Water heater	Load shed/ Load up command

Possible Parameters of DER Interfacing with DERMS

- Active power setpoints
- Active power limits
- Reactive power setpoints

DER Models

PV system

Since PV output is dependent on the weather conditions and irradiance, the model of PV solar inverter only depends on its nameplate ratings. The apparent power of inverter is defined as:

$$S = sqrt(P^2 + Q^2)$$

The PV system physical model parameters are defined in Table 12.

Table 12. PV Physical Model Parameters

Parameter	Units	Definition
P	Watts	Active Power
Q	VAR	Reactive Power
S	VA	Apparent Power

Energy storage

Energy storage is modeled to receive a charge or discharge setpoint and dispatches power according to its capacity and nameplate ratings. The resultant state of charge of the battery is updated and provided to the upstream managing entity as required. The energy storage model's physical model parameters are defined in Table 13.

Table 13. Energy Storage Physical Model Parameters

Parameter	Units	Definition
EFF_C	Percentage	Charging efficiency
EFF_D	Percentage	Discharging efficiency
EFF_RT	Percentage	Roundtrip efficiency
SOC_MAX	Percentage	Maximum state of charge
SOC_MIN	Percentage	Minimum state of charge
PCAP_C	Watts	Maximum power capacity when charging (at the grid)
PCAP_D	Watts	Maximum power capacity when discharging (at the grid)
ECAP	Watts Hour	Discharge Energy capacity of the system
SELF_D1	1/hr	Self-Discharge Rate (SOC-dependent)
SELF_D2	Percent/hr	Self-Discharge Rate (constant)
SOC(t)	Percentage	Energy state of charge at the end of time interval
Δt	Hour	Sampling period for simulation
C_G(t)	Watts	Charging power during time interval t (at the PCC)
D_G(t)	Watts	Discharging power during time interval t (at the PCC)

Energy storage: Physical model

The energy storage is a dynamic, time-coupled model that changes its state based on the input power signals and physical model parameters. The energy storage is modeled as a discrete-time dynamic system that provides input and state constraints. The model is defined as follows. The state of charge of ES system is defines as:

$$\mathrm{SOC(t)=SOC(t\text{-}1)}+\left(\frac{\mathrm{EFF\_RT}}{\mathrm{ECAP}}C\_G(\mathrm{t}) - \frac{1}{\mathrm{ECAP}}D\_G(\mathrm{t}) - \mathrm{SELF\_D1}\times\mathrm{SOC(t\text{-}1)} - \mathrm{SELF\_D2}\right)\times\Delta\mathrm{t}$$

for all t, where EFF_RT is the roundtrip efficiency defined as $EFF\_C \times EFF\_D$.
Charging and discharging values are calculated according to the equation below:

$$C\_G(t) = min\left(\left[\frac{SOC\_MAX - SOC(t-1)}{\Delta t} + SELF\_D1 \times SOC(t-1) + SELF\_D2\right]\frac{ECAP}{EFF\_RT}, PCAP\_C, C_t^{SP}\right)$$

$$D\_G(t) = min\left(\left[\frac{SOC(t-1) - SOC\_MIN}{\Delta t} + SELF\_D1 \times SOC(t-1) + SELF\_D2\right]ECAP, PCAP\_D, D_t^{SP}\right)$$

Controllable Loads

Water Heater

The modeled Electric Water Heater (EWH) is applicable to three types of water heater:

- Electric Resistive Water Heater (ERWH)
- Heat Pump Water Heater (HPWH)
- Heat Pump with Resistive boosting element (HPRWH).

The EWH complies with the standard and specifications from Energy Star and CTA-2045 [1, 2]. The inputs required for EWH are hot water draw, and “Event types”, i.e., “Normal operation”, “Shed”, etc. Time variable outputs, based on model calculation, include instantaneous power, water temperature in the tank, and energy take, etc. The EWH model’s physical parameters are defined in Table 14.

Table 14. Electric Resistive Water Heater Model Physical Parameters

Parameter	Units	Description
DEN_W	Kilogram per cubic meter (kg/m3)	Density of water
SHC_W	Joule per kilogram degree Celsius (J/(kg *°C))	Specific heat capacity of water
EWH_TYPE	-	ERWH | HPWH | HPRWH
VOL_W	Gallon (gal)	Capacity (water)
V_EWH	Volt (V)	Rated voltage for EWH
PH_EWH	-	Phases for EWH
UEF_ER	-	Uniform energy factor (ERWH, HPRWH)
UEF_HP		Uniform energy factor (HPWH, HPRWH)
WATT_ER	Watt (W)	Element power rating (ERWH, HPRWH)
WATT_COM	Watt (W)	Compressor power rating (HPWH, HPRWH)
WATT_EWH	Watt (W)	Real EWH heating rate
EQUIV_RTH	Degree Celsius per kilowatt (°C/kW)	Equivalent thermal resistance for insulation
EQUIV_CTH	Kilowatt hour per degree Celsius (kWh/°C)	Equivalent thermal capacitance
ET_EWH	-	Event type
F_HPRWH	-	Operation mode for HPRWH
HWD	Cubic meter per second (m3/s)	Hot water draw
TEM_EWHU	Degree Celsius (°C)	Upper setting point
TEM_EWHL	Degree Celsius (°C)	Lower setting point
TEM_R	Degree Celsius (°C)	Room air temperature
TEM_CW	Degree Celsius (°C)	Temperature of cold water
EWH_ON	Bool	EWH operation flag
OP_EWH	-	Operating state
P_EWH	Kilowatt (kW)	EWH power (instantaneous)
TEM_TANK	Degree Celsius (°C)	Water temperature in the tank
ETAKE_EWH	Watt hour (Wh)	Energy take

All the parameters for the EWH model are defined in the table.

Water heater: Physical model

The thermodynamic of an EWH is represented by a first order equation that quantifies the relationship between tank temperature and energy applied to the EWH. The first order equation majorly considers the power input of the heating element, standby loss, and how water usage. The generic EWH model is defined as:

$$
\begin{aligned}
EQUIV\_CTH \times \frac{\mathrm{d}TEM\_TANK(t)}{\mathrm{d}t} \\
&= EWH\_ON(t) \times WATT\_EWH \\
&- \frac{1}{EQUIV\_RTH} \times [TEM\_TANK(t) - TEM\_R(t)] \\
&- DEN\_W \times SHC\_W \times HWD(t) \times [TEM\_TANK(T) - TEM\_CW(t)]
\end{aligned}
$$

The above EWH model can be applied to ERWH, HPWH, and HPRWH by setting up the parameters, accordingly. For example, a typical value for EQUIV_RTH is 1500 °C/kW for ERHW, and 700 °C/kW for HPWH and HPRWH. The parameter "Operation mode for HPRWH", F_HPRWH, has two bits, which stand for the On/Off status of compressor and boost heating element of the HPRWH, respectively. The F_HPRWH has the following values:

- (1,0), compressor is on and boosting element is Off,
- (1,1), both compressor and boosting element are On.

The model calculates internally the WATT_EWH, which is the heating rate transferred to the water in the EWH tank, For all three types of EWH, the WATT_EWH are different as they use the resistive heating element, compressor, or both, for heating, respectively, as:

- WATT_ER×UEF_ER for ERWH, as the real heating rate is decided by the rated element power and heating efficiency
- WATT_COM×UEF_HP for HPWH, as the real heating rate is decided by the rated compressor power and the COP
- [WATT_COM ×UEF_HP + WATT_ER×UEF_ER] · F_HPRWH, as it is the combination of resistive heating element and compressor.

HVAC system

To model a full HVAC system, it must be linked to a full building profile within which it operates. This link is due to the significant relationship between HVAC operation and the thermal conditions of the building, which are determined by the building climate and construction. Therefore, the HVAC system and its associated thermal loads are simulated as a building information model (BIM) using EnergyPlus (EP), which is a whole building energy simulation program that models both energy consumption and loads in buildings. The model is initialized by three predefined files, which include the comprehensive EP input data file (IDF) defined in Table 10,, EP weather data file (EPW) defined in Table 11, and domestic hot water (DHW) usage schedule.

The EP IDF contains very extensive information about the simulated building construction materials as well as specifications for the HVAC system and other related devices. IDF parameters relevant to the HVAC system and building modeling are provided in Table 15Table 10.

Table 15. EnergyPlus Input Data File Parameters Relevant to the HVAC System and Building Modeling

Component	Required parameters for BIM	Preferred parameters for BIM
Floor plan	Building size, # of floors	Room sizes/locations
Wood stud	R-value, material, size	On center (o.c) distance
Exterior finish	Finish type	Absorptivity rating and R-value
Attic	Insulation type, finished or unfinished, R-value, vented or unvented	N/A
Roof Material	Shingles type	Color and absorptivity
Slab	Perimeter and Gap R-value	Perimeter insulation width
Window area	Total ft^2	Front, Back, Left, Right, etc.
Window	Pane type, U-Factor, Solar Heat Gain Coefficient (SHGC)	N/A
Doors	Amount	Total ft^2
Air leakage	Air changes per hour at 50 pascals (ACH50)	N/A
Ventilation	Fan type	Total recovery efficiency, if any
Cooling/heating	HVAC type, SEER, HSPF, capacity, number of speeds, COP for each speed	N/A
Ducts	Leakage %, R-value	Location
Water heater	Type	Size, setpoint, efficiency
Appliances	N/A	Model/type, hot water use schedule, energy use
Lighting	N/A	Type, energy use
Plug loads	N/A	Energy use

The EPW file provides in-depth weather data to the building simulation so that the modeling of thermal conditions and HVAC system operation are accurate. The weather data included in an EPW file is summarized in Table 16.

Table 16. Weather Data Details Included in an EPW File

Weather parameters	Requirement
Outside Temperature {C}	Required
Outside Relative Humidity {%}	Required
Direct Normal Radiation {W/m2}	Required
Wind Direction {degrees}	Required
Wind Speed {mph}	Required
Dew Point Temperature {C}	Preferred
Atmospheric Pressure {Pa}	Preferred
Extraterrestrial Horizontal Radiation {Wh/m2}	Preferred
Extraterrestrial Direct Normal Radiation {Wh/m2}	Preferred
Horizontal Infrared Radiation Intensity from Sky {Wh/m2}	Preferred
Global Horizontal Radiation {Wh/m2}	Preferred
Diffuse Horizontal Radiation {Wh/m2}	Preferred
Global Horizontal Illuminance {lux}	Preferred
Direct Normal Illuminance {lux}	Preferred
Diffuse Horizontal Illuminance {lux}	Preferred
Zenith Luminance {Cd/m2}	Preferred
Total Sky Cover {.1}	Preferred
Opaque Sky Cover {.1}	Preferred
Visibility {km}	Preferred
Ceiling Height {m}	Preferred
Present Weather Observation	Preferred
Present Weather Codes	Preferred
Precipitable Water {mm}	Preferred
Aerosol Optical Depth {.001}	Preferred
Snow Depth {cm}	Preferred
Days Since Last Snow	Preferred
Albedo {.01}	Preferred

To enable demand response capabilities, the HVAC system model can receive an indoor temperature setpoint change request between simulation timesteps. This allows for "Event types", i.e., "Normal operation", "Shed", etc., as per Energy Star and CTA-2045 [12,13] to be executed through an interface with L-DERMS. Furthermore, L-DERMS may receive the HVAC

[12] "CTA standard: Modular communications interface for energy management," Consumer Technology Association (CTA), Tech.Rep., 2020.

[13] "Energy star water heaters - test method to validate demand response," https://www.energystar.gov/products/spec/residentialwaterheatersspecificationversion30pd, accessed: 2021-2-9.

system simulation outputs at each timestep so that it may determine the appropriate temperature setpoint change request that will execute its desired event type. The HVAC system parameters exchanged with L-DERMS are summarized in Table 17Table 12.

Table 17. Parameters Exchanged Between EnergyPlus and L-DERMS

Parameter	Units	Description
TEM_O	Degree Celsius (°C)	Outdoor temperature
RH_O	Percentage (%)	Outdoor relative humidity
WS	Meter per second (m/s)	Wind speed
WD	Degree (°)	Wind direction
HVAC_ON	Bool	HVAC operation flag
P_HVAC	Kilowatt (kW)	HVAC power (instantaneous)
TEM_R	Degree Celsius (°C)	Indoor air temperature
RH_I	Percentage (%)	Indoor relative humidity
TEM_SET	Degree Celsius (°C)	Temperature setpoint change

*if the file is not available, a generic file is provided based on the number of references. The occurrence of the building will be affected in such case.

Examples of comprehensive building simulation files are provided in native IDF format. Example EPW files are also available and custom versions may be developed based on locally measured historic weather. Since DHW usage is mostly dependent upon human behavior and minimally influenced by climate, a generalized DHW schedule file developed based upon information provided by the Building America program[14] is utilized for simulation.

[14] "Building America," https://www.energy.gov/eere/buildings/building-america, accessed: 2021-3-17.

8
APPENDIX C: SCHEDULE ARRAY MESSAGE DETAILS

Schedule array is defined as an array of N schedule points of power service request can be defined in two formats. A planned schedule array can be exchanged in different formats. Each of the formats are described below.

Table 18 shows format I for sending a planned scheduled array. In this format, the starting time of settings value is received as a single row of data and the duration for which the settings value needs to remain active is received as the following row of data where the settings value is replaced as None. If None is not defined, then the prior setting value would remain active for an indefinite amount of time and it is possible that the managed entity might run out of capacity over time.

Table 18. Planned Schedule Array Format I

Start time	Scheduled parameter values
t1	Settings values 1
T1+deltaT1	None
t2	Settings values 2
…	…
tN	Settings values N
tN + deltaN	None

Table 19 shows format II for sending a planned scheduled array. In this format, the starting time and duration of settings value is received as a single row of data. The setting value is active from the start time to start time + duration. For example, setting value 1 is starting at t1 it will continue to operate until t1+deltaT1. The following setting value 2 would start at t2 and would remain active until t2+deltaT2.

Table 19. Planned Schedule Array Format II

Start time	Duration	Scheduled parameter values
t1	deltaT1	Settings values 1
t2	deltaT2	Settings values 2
…		…
tN	deltaTN	Settings values N

If an instantaneous service requests is received, then in both the formats the schedule array will consist of only one setting value where start time *t* will be same as the current time of the system as shown in Table 20 and Table 21.

Table 20. Instantaneous Schedule Array Format I

Start time	Scheduled parameter values
t	Settings values 1
t+deltaT	None

Table 21. Instantaneous Schedule Array Format II

Start time	Duration	Scheduled parameter values
t	deltaT	Settings values 1

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