



Communication Utility DERMS for Active Management of Emerging Distribution Grids with High Penetration of Renewable DERs

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Abstract: Operational and planning challenges caused by ever-increasing integration of electronically coupled renewable distributed energy resources (DERs) have become a reality all over the globe. These challenges range from technical constraint violations to malfunctional setting and coordination of the protective equipment and inaccurate operational planning. Moreover, to enable the preconditions for the integration of high penetration of renewable DERs, utilities are faced with potentially huge investment requirements in strengthening the grid assets. However, recent advances in specialized software solutions for integration and active management of high penetration of DERs could turn these challenges into operational and monetary benefits. Hence, if planned, managed, and operated in an optimal way, the high penetration of DERs could be a valuable resource for increasing the efficiency of the overall management of distribution grids. Utility distributed energy resource management systems (utility DERMSs) aim to provide all of these capabilities integrated into a single software solution. In this paper, a utility DERMS concept is introduced, and the capabilities of state-of-the-art utility DERMS solutions for helping the key stakeholders to pave the way towards stable, optimal, and secure emerging distribution systems with high penetration of electronically coupled renewable DERs are explored.

Keywords: distributed generation; distributed energy resource; DERMS; distribution management system; electronically coupled DERs

1. Introduction

The traditional method of producing electric power and supplying it to the end customers was straightforward: The electricity was produced in bulk by large power plants, transmitted through high-voltage lines to the supply stations, and then distributed to end customers through distribution lines. Power flows at the distribution system level were in one top-down direction—from the supply station to the end customers with a predictable voltage drop occurring along the feeders. Therefore, the traditional voltage-regulating devices (load tap changers, voltage regulators, capacitor banks, etc.) were located at predefined positions, and were fully able to maintain voltages within the required boundaries [1–4]. Protection equipment was traditionally located at predefined critical locations, and was set to react to predictable and unidirectional fault currents (from the supply station to the fault location). Distribution protection, control, and metering were handled by electromechanical devices, and almost no automation existed at the traditional distribution systems' level [1–4]. Consequently, distribution network operators (DNOs) at that time were fully able to manage their corresponding grids manually, applying traditional paper-driven processes, without the need for almost any interactive action in real time [1–5].

Today, a huge paradigm shift in distribution system structure and operations is underway. Ever-increasing penetration of distributed energy resources (DERs) is rapidly



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). transforming the landscape of distribution grids towards active, dynamically changing systems. In today's terminology, a DER can refer to various types of resources, with different characteristics and implementing vastly different technologies. All types of distributed generation (DG)—such as solar panels, wind turbines, small hydro power plants, combined heat and power (CHP) units, etc.—are DERs. Furthermore, different types of energy storage systems—such as batteries or flywheels—are also considered to be DERs. Moreover, electrical vehicles (EVs) and electric vehicle charging stations are DERs as well. Finally, demand response (DR) and even energy efficiency programs are considered to be DERs today [5]. Hence, as various novel and very different types of resources, with completely distinct natures, are being actively connected to distribution grids, it is obvious that they impose new challenges that traditional distribution network operators are not accustomed to [3,5]. Furthermore, it is shown in [6] how DR initiatives with advanced control algorithms enable much safer and easier integration of individual DERs into the microgrids, envisioning an exponentially increased integration of renewable DERs with adoption of these advanced techniques.

Nevertheless, the rapid increase in DER integration around the globe is being driven by the low-carbon and energy efficiency initiatives introduced all over the world, as well as by the pollution problems caused by fossil-fuel-based power plants and traditional gasfueled vehicles. However, even though the integration of high penetration of renewable DERs is crucial, and the energy transition should be swiftly performed, renewable DERs are introducing significant challenges that need to be considered and properly addressed in order to avoid the catastrophic consequences of leaving the grid and the utility personnel unprepared for these significant changes. As most of the renewable DERs (solar PVs, modern wind turbines—types 3 and 4)—as well as batteries, microturbines, EV chargers, etc.—are electronically coupled (i.e., connected to the grid via inverter) and, thus, operate in a significantly different manner relative to the traditional AC machines, new control techniques need to be adopted for the proper and safe management of high penetration of electronically coupled renewable DERs [7]. As this is completely different way of connecting active resources to the power systems (relative to the traditional AC machines that are directly connected to the grid), electronically coupled DERs introduce most of the challenges to the DSOs, and will be mostly addressed in this paper. In the following text, the term "electronically coupled" will scarcely be used, in order to avoid overburdening the paper, but as most of the DERs are connected to the grid by inverters, the vast majority of the following discussion regarding DERs applies to electronically coupled DERs.

Furthermore, because renewable DERs are variable by nature, and as the periods of usage of electric vehicles are difficult to be predict, these emerging resources introduce a high level of uncertainty and variability into the operation of distribution networks [5,8]. Moreover, the optimal coordination of using these resources needs to be adapted in real time, so a much greater interoperability is required by operators. Further, recent initiatives for grid automation and modernization, applied by the integration of remotely controlled regulation and protection devices, calls for a much better ability to monitor and control distribution grids. Nevertheless, in order to avoid the expense of building new assets, existing feeders are loaded more heavily, closer to their limits [1–5]. This additionally complicates traditional switching procedures, as operators can no longer count on having a plenty of spare capacity on adjacent feeders to perform load transfers for satisfying various other objectives.

To bridge the gap between traditional practices for managing distribution networks, and emerging challenges caused by integration of high penetration of DERs, traditional DNOs need to shift towards much more involved operators, called distribution system operators (DSOs).

To secure reliable, protected, and optimal operation of distribution systems, DSOs must provide [1–5]:

1. Reliable and affordable grid operations:

- Ensure that the grid operates within technical and operational limits, providing reliable supply to customers within acceptable voltage limits;
- Ensure that the grid remains secure against any unpredictable circuit trips and generation losses;
- Ensure coordination with transmission system operators (TSOs) to support overall system optimization objectives;
- Enhance system security through the provision of flexible local and regional customer services;
- Respond to customer needs in real time and engage the customers in provision of aggregated flexibility for system-wide needs.
- 2. Network investment planning:
 - Identify requirements for grid capacity in order to host new DERs;
 - Identify system-wide options for capacity provisioning, including flexible customer services that may help in reducing traditional network investments;
 - Intelligently plan the utilization of the flexibility of existing DERs, as well as of DERs planned to be integrated, in order to enable non-wires alternative (NWA) methods of increasing the system hosting capacity.

It can be concluded that an accurate estimation and optimal usage of the flexibility of DERs will be the key requirement of the emerging DSOs, in order to satisfy most of the requirements of emerging distribution utilities [9–11]. Moreover, as the requirements of much tighter TSO–DSO integration are emerging around the globe, as well as the requirements that DSOs provide the aggregated DER flexibility for the TSOs' needs, estimation of the accurate flexibility in near-real time, and in the short-term future, will soon become a prerequisite for the emerging DSOs [11]. Furthermore, as DSOs need to provide much more advanced services, and as they need to be alert and able to react to dynamically changing conditions in real time by using the flexibility of the available DERs, a more sophisticated, intelligent, and digital means of managing distribution systems will soon become crucial for DSOs [10].

Fortunately, emerging software solutions called utility distributed energy resource management systems (utility DERMSs) aim to provide all of these capabilities and enable the critically important DNO-to-DSO transformation. The capabilities of utility DERMS solutions in enabling the proper planning and active management of emerging distribution grids with high penetration of renewable, electronically coupled DERs are the main subject of this paper. The main aims of the paper are to draw the attention of the power system community and industry to the novel concept of DERMSs; to clearly distinguish between various different software hierarchies that are often simply called DERMSs, but have vastly different capabilities and goals (i.e., utility DERMSs and DER aggregators); and, finally, to present how DERMS solutions can work in coherence and, if intelligently used, can enable a much-needed DNO-to-DSO transformation. This paper is a natural extension of the authors' research published in [12], where a utility DERMS concept was first introduced, and which has already gained significant attention in the power system community and industry.

The rest of the paper is organized as follows: In Section 2, the most critical challenges caused by renewable DERs are summarized. In Section 3 the DERMS is defined, with the focus on distinguishing the responsibilities and capabilities of different types of DERMS solutions (i.e., DER aggregators and utility DERMSs). In Section 4, the capabilities of utility DERMSs to provide active network management functionalities to DSOs are discussed. In Section 5, several representative use-cases that provide an insight into the benefits that DSOs can gain by implementing utility DERMS solutions are presented, whereas a real-life example of actively managing the flexibility of DERs by operating an integrated utility DERMS and DER aggregator solution to manage the grid constraints is presented in Section 6. The results of a numerical example are discussed in Section 7, while the paper is concluded in Section 8.

2. Critical Challenges Caused by DERs

Challenges caused by DERs vastly differ in terms of their specific cause and nature. DGs and energy storage systems, when left to operate stochastically, introduce serious technical challenges, as these types of DERs may cause overloads on the existing feeders as well as considerably increasing voltages at their connection points [8,11–15]. Furthermore, in periods of low demand but high production of renewable DGs (e.g., high sun irradiation or wind power), a new phenomenon of reverse power flow occurs [8,11–15]; that is, during these critical periods, the excess power produced by renewable DERs flows from distribution to transmission systems, for which traditional electrical systems were not designed and can cause many undesirable consequences. Reverse power flow may cause maloperation of the protective equipment, as well as unexpected voltage variations along the feeders. Moreover, because of their volatile nature, renewable DGs may cause high levels of uncertainty in their production and, therefore, if left unmanaged, can cause issues in forecasting of generation as well as in distinguishing between net and gross demand, consequently causing challenges in both the short- and long-term operational planning of distribution systems [14,15]. Furthermore, as the behavior and charging patterns of EVs can be almost completely stochastic and hard to predict with traditional forecasting methodologies, if left unmonitored and poorly managed, high penetration of EVs and EV charging stations can cause considerable challenges for system operators in the attempt to properly balance and manage their corresponding electrical systems. In addition, as the most of the renewable DERs are connected to the distribution grid through power electronic devices, their fault currents are limited, and much lower than the fault currents of traditional synchronous machines, which can cause maloperation of the relay protection and its coordination [16]. Finally, the dynamical behavior of today's systems caused by ever-increasing penetration of volatile DERs, EVs based on cutting-edge technology and able to operate in a "vehicle-to-grid (V2G)" mode, and other dynamic loads connected through power electronic interfaces introduce another paradigm shift in managing and operating the electrical systems; that is, the traditional ever-increasing load of several percent each year is rapidly fading away [1]. In today's world of numerous small DG units, behind-the-meter and large-scale energy storage, and electrical vehicles in V2G mode, the load increase becomes minimal or even negative [11]. Thus, traditional balancing mechanisms of using huge coal or nuclear power plants are no longer suitable, and new means of fast and flexible balancing services must emerge [12–17]. At the same time, distribution utilities will need to enable customer participation in new markets, including flexibility markets, as well as their participation in the wholesale electricity market. The flexibility markets will play a vital role for DSOs to procure flexible services from customers and DERs to manage their corresponding distribution systems and keep them within the required boundaries. Flexibility and flexible services are becoming the core of distribution system management, which would enhance the capability of DSOs to manage the grid while ensuring reliable and efficient operation of the distribution system as a whole, while also improving hosting capacity and maximizing renewable production by enabling new customer connections to the existing grid.

With a rapidly increasing penetration of DERs, these challenges are becoming a huge concern for DSOs around the globe, and initiatives to develop proper solutions to cope with them are well underway. A significant portion of these initiatives, promising to turn the potentially dangerous behavior of DERs into advantages—and even operational and monetary benefits, for both DSOs and end customers—is the emergence of utility DERMS solutions.

3. Defining Utility DERMSs

As the concept of DERMSs is still emerging, its definition is frequently quite vague. As the name suggests, DERMS corresponds to a software solution for managing DERs [3,12–15]. However, the term DERMS is frequently labeled to several significantly distinct levels of software hierarchy. On the one hand, there are decentralized software solutions for

the aggregation of large amounts of small-scale, behind-the-meter resources—such as air-conditioning or heating systems, rooftop solar panels, small energy storage systems, or EVs—with the aim of providing their services in an aggregated and much more useful manner, i.e., entering the electricity market or providing demand response and energy efficiency programs, among others.

On the other hand, there are centralized enterprise solutions providing situational awareness, manual/automatic DER control, constraint resolution, and advanced optimization applications for the efficient management of medium-to-large-scale DERs and DER groups consisting of numerous small-scale units, with the aim of providing technical, operational, and monetary benefits to the DSO.

In Table 1, different DER management solutions, with completely different goals and aimed at vastly different stakeholders, are described. Additionally, a hierarchical structure of these different solutions is denoted (centralized or decentralized solutions).

| Stakeholder | Goal | Centralized/ Decentralized |
|---|--|-------------------------------|
| Transmission system operator (TSO/ISO) | Supply/demand balancing; ancillary services; flexible capacity to meet peak demand and cope with demand and renewable variability, etc. | Centralized |
| Distribution system operator (DSO) | Relieve congestion and voltage violations; defer network reinforcement (CAPEX); enhance distribution grid hosting capability, optimization, grid edge stability, etc. | Centralized |
| Market participants and market operators | Wholesale: optimize portfolio (risk management) and minimize imbalance costs; Retail: hedge against high wholesale prices; support new retail tariffs and competitive differentiation | Decentralized |
| Prosumers, microgrid DERs, DER communities | Aggregate DERs for local energy management, including microgrids, to optimize costs (energy and demand charges), integrate DG/renewables, and improve resiliency | Decentralized |

Table 1. Different DER management solutions and their goals.

It is very important to emphasize at this stage that both centralized and decentralized DER management solutions are very important to enable a safe energy transition towards sustainable and clean power systems. However, the fact that all of these solutions are often simply called "DERMSs" can be confusing and lead to misunderstanding among the key stakeholders (i.e., electric utilities, microgrid owners, market participants, etc.) regarding which solution is the most suitable for their needs. Thus, in the following text, a clear distinction between different levels of hierarchy among DER management solutions will be made.

Two borderline cases, which are both frequently simply called "DERMSs", are DER aggregators and utility DERMSs. While their aims might seem similar, these two solutions differ widely in nature and responsibilities. However, if integrated in an intelligent manner, these two solutions can perfectly complement one another in securing the full spectrum of services essential for contemporary DSOs, responsible for ensuring safe, secure, and optimal management of an ever-increasing penetration of DERs.

3.1. Utility DERMS and DER Aggregators

The main aim of DER aggregators is to aggregate small, usually behind-the-meter DERs into DER groups, and then provide various services to customers and to the DSO,

using the aggregated DER power. Services offered by DER aggregators include market participation, customer engagement in energy saving schemes, provision of demand response and load shedding programs, and other, mostly customer-related services. However, DER aggregators usually do not have access to an accurate network model, and are unaware of the grid-level technical constraints, such as transformer and line overloads, voltage limits, or reverse power flow constraints. This is where the utility DERMS comes into play.

A utility DERMS is an intelligent software platform for the optimal management of medium-to-large-scale DERs, as well as DER groups that are constructed of small-scale DERs and aggregated via DER aggregators, with to the aim of using all of these resources to achieve system-wide benefits without violating operational constraints, as it is completely grid-aware. Moreover, utility DERMSs use all of their resources to solve already violated or intelligently predicted constraint violations, and to keep the system in a stable and optimal state. Thus, regarding large- and medium-scale DERs whose impact on the grid conditions can be significant, a grid-aware utility DERMS is a natural environment for their management and control.

Hence, from the DSO's standpoint, utility DERMSs and DER aggregators should be understood as different levels in a hierarchy: DER aggregators mainly communicate with behind-the-meter units and use them in an aggregated fashion to provide various services regarding customer engagement and operations, whereas utility DERMSs use DER aggregators—among other resources, such as individual medium-to-large-scale DERs, various types of DER groups, virtual power plants (VPPs), microgrids, and traditional resources such as switches, capacitors, etc.—to provide DSOs with complete awareness, effortless real-time and look-ahead constraint management, optimal coordination and management of DERs and DER groups, and other system-wide operations. Therefore, if properly integrated, DER aggregators and utility DERMSs perfectly complement one another, and can provide a full spectrum of DER services regarding both customer- and grid-related operations, regardless of the DERs' sizes and locations [18].

3.2. Active Network Management

As thoroughly discussed in the above section, utility DERMSs aim to monitor, control, and optimally coordinate the response of DERs and DER aggregators on a global (systemwide) scale, and to be aware of and able to solve all technical and other system-wide violations in real time. To do so, utility DERMSs should consist of several modules integrated into a single solution. In addition to having sophisticated DER awareness and control capabilities, these modules should consist of constraint management, smart inverter control and coordination, DER flexibility utilization, optimal DER planning, etc. A new term-"active network management (ANM)"-is coined for a set of functionalities that include the capabilities of all of these modules [13,19–21]. Through utility DERMSs, distribution utilities have a complete set of active network management capabilities at their disposal. The vital role of active network management is to manage network constraints arising from general load variation or excess renewable generation or DER variability by combining traditional network assets and DER flexibility. If the export or import of DERs can be optimized or managed in a flexible way, it would provide an opportunity for DSOs to leverage more of the existing network capacity, deferring the need for investment in the network augmentation. Thus, if used when a distribution network does not have further capacity to accommodate unlimited import or export from a new customer or DER connection, the ANM enabled through the utility DERMS can provide significant benefits for both DSOs and end customers. The intelligent management of the customer/DER flexibility is enabled through flexible connections and flexible services. Customers with flexible connections voluntarily opt into arrangements where their access to the distribution network can be constrained at times of peak power flows, in return for faster connections at a reduced capital cost. Flexible services mean procuring DER flexibility from customers behind constraints through the local flexibility market; this means that the DSO pays for that service, but it is still a highly cost-effective alternative method (relative to huge investments

in strengthening the grid assets) to relieve constraints and, ultimately, minimize costs to consumers [20].

A high-level architecture of the utility DERMS solution, with the main communication channels and required capabilities, is depicted in Figure 1 [21].



Figure 1. High-level architecture of a utility DERMS solution.

4. Active Network Management through Utility DERMS Solutions

In this section, the capabilities of state-of-the-art utility DERMS solutions to overcome DER-imposed challenges and provide ANM functionalities to DSOs are discussed. Through these provisions, utility DERMSs represent a key solution that utilizes all available resources—including traditional ones such as load tap changers, voltage regulators, switches, and capacitors, in an optimal mix with DERs' and DER aggregators' flexibility in increasing distribution systems' efficiency and transforming the emerging challenges into the benefits for both DSOs and end customers.

Clearly, to enable all of the following advanced functionalities, the utility DERMS must be fully grid-aware and able to provide complete and accurate real-time and forecasted awareness of the conditions in the grid; that means having an accurate network model with precise representation of all of the elements, the ability to ingest all of the available measurements from the field, and integration capabilities with weather providers. On top of that, accurate load flow, state estimation, and load and generation forecast functionalities are the foundation on which all of the advanced applications for ANM are dependent. In the following section, the specific modules of utility DERMSs for providing ANM features are discussed.

4.1. Constraint Management

Constraint management is one of the core modules within utility DERMSs. With increased penetration of DERs, the conditions in the grid have become highly dynamic, and DSOs need to respond to these changes in real time [14]. This is where advanced applications within utility DERMSs become essential. By monitoring system conditions in real time, and applying advanced real-time applications—such as load relief, volt/VAR watt optimization, and adaptive relay protection—in a closed loop, utility DERMSs use all available resources to automatically solve overloads, over/under-voltages, and reverse power flows, as well as miscoordination of the protective devices in real time. These applications react to any violation by utilizing an optimal mixture of traditional resources, as well as DERs, DER aggregators (including the microgrids and VPPs), and DR programs to find the best and the most cost-effective solution to the existing problem, and automatically solve or prevent it in real time.

Moreover, by implementing sophisticated short-, medium-, and long-term load and generation forecasts, utility DERMSs considerably decrease uncertainty introduced by DERs, allowing their planned and coordinated utilization in current and future periods [22–24]. Finally, utility DERMSs should provide a look-ahead constraint management module, which utilizes an optimal mixture of advanced applications and cutting-edge load and generation forecast to predict and proactively solve detected future violations. This module allows DSOs to predict the upcoming issues beforehand, and proactively react by amending schedules and active set points on DERs and DER aggregators, in order to avoid potential issues altogether.

4.2. Utilizing Smart Inverter Capabilities

Today, most renewable DERs are connected to the grid through smart inverters [19]. Smart inverters are power electronic devices with advanced control capabilities, designed to respond to external conditions or commands in real time. Examples of smart inverter control capabilities range from services to aid normal system operation—such as autonomous adjustment of their reactive power output to help in maintaining the allowed voltage level in the local area—to supporting system reliability by allowing DERs to safely ride through faults and aid with the faster voltage recovery after the fault [1,2,13]. Moreover, smart inverters can be programmed to follow the commands of a centralized control system, such as a utility DERMS [13].

As utility DERMSs are fully grid-aware, they can orchestrate the output and behavior of smart inverters to provide system-wide benefits. To prevent uncoordinated behavior of local automation that can cause issues on a system-wide level, utility DERMSs observe and update the inverters' set points—as well as their preset behavior (e.g., volt/VAR curves)—in real time, and utilize smart inverters along with traditional resources (e.g., load tap changers, voltage regulators, capacitor banks, switches, etc.) on a global level to satisfy system-wide optimization criteria. Moreover, in contingency conditions, utility DERMSs can issue emergency commands that override inverters' local autonomous control logic and use inverter-based DERs as resources to help achieve faster recovery from contingency events. Thus, even though smart inverters are beneficial assets by themselves, they alone can provide only limited and localized benefits. Nevertheless, if monitored and controlled in real time by a centralized software solution that is fully grid-aware, the full range of their capabilities can be exploited, and the overall system efficiency would be tremendously increased.

4.3. Utilizing DER Flexibility

To respond to significantly dynamic changes in today's system operation and balancing needs, DSOs can no longer rely on slow, costly, and inflexible large-baseload power plants [19]. Having a large amount of power from traditional plants coming into the grid every minute is not desirable in today's dynamic conditions. Instead of being forced to design a grid around these huge, inflexible sources of power, DSOs are turning towards much more flexible and readily available small- and medium-scale DERs [19–21]. An indicative example of this paradigm shift is Pacific Gas and Electric's decision to decommission the 2.2-GW Diablo Canyon nuclear plant and use renewable DERs instead [20].

However, coordinating a huge amount of DERs and effectively using their flexibility is not an easy task. This cannot be executed without having a highly intelligent and centralized software platform to guide DSOs in performing these highly complex tasks. This is where utility DERMSs value is apparent; as they are always aware of the flexibility of DER aggregators, DR programs, utility-controlled DERs, and DER groups, in both current and look-ahead periods, utility DERMSs represent a perfect solution for DSOs to efficiently provide balancing services to the responsible balancing providers. That, in addition to being aware of current and future system-level constraints, as well as of forecasted demand increase/decrease, provides a tremendous opportunity for the DSOs to utilize these highly flexible resources instead of large power plants for satisfying system balancing needs, and in this way increase the overall power system efficiency. Moreover, by organizing various sources of renewable generation with energy storage systems into VPPs, and then optimally managing the output of multiple VPPs, utility DERMSs can provide virtually the same services as would be provided by baseload power plants, but in a much more rapid, efficient, and pollution-free way.

4.4. Provision of Flexible Contracts and Services

Due to the many new DER connection requests received daily, planning departments within electric utilities are faced with an inevitable need for grid reinforcements to improve their system hosting capacity [24-26]. These reinforcements can require significant capital investments, for which some utilities are not currently prepared, or else wish to avoid them altogether. Moreover, even if the utilities are apt to invest in the grid, building new substations, lines, etc. from scratch could take a long time to pass all the regulation requirements and obtain the required permits, and would therefore significantly defer DER connections. Fortunately, there are other ways to achieve the same goals with significantly lower—or at least, different—expenditure. A considerable part of today's ANM requirements is offering "flexible contracts" to new customers, by which the operators would be allowed to limit, curtail, or alter DERs' production in critical periods and, in this way, satisfy system constraints without actually reinforcing the grid with new assets [24–26]. By doing so, new DERs would be allowed to connect, and most of their potential would be used, but without violating constraints. Furthermore, these specialized contracts could contain a time clause, where after the pre-defined time period required for the operator to reinforce the grid, DERs would always be allowed to produce their full capacity. Finally, through flexible contracts, DSOs can settle with DER owners to pay for their services, in agreed periods and for agreed amounts of energy, thus compensating for unused DER energy [23–26].

The essential interface between the new customers and the utilities is achieved through utility DERMSs, where new customers can observe system hosting capacity availability online and send requests for new connections, while the planning engineers would validate these requests and notify the customers of the availability and the required preconditions. Moreover, after the new connection is approved, the utility DERMS can be used for monitoring, limiting and, in worst case scenarios, curtailing DERs, as per the predefined rules from the flexible contracts. Hence, all of the conditions required to successfully implement the flexible contracts, from pre-contractual terms to the actual implementation in the field, can be efficiently achieved through utility DERMSs. Finally, flexible service provides the ability for customers to alter their consumption or production as a service. Flexibility services can be offered on local flexibility markets. The flexibility markets are new, emerging marketplaces for DSOs to procure flexibility from flexible providers (e.g., customers, DERs, DER aggregators) to alleviate network congestion in real time. DSOs pay for these services and utilize them in critical situations when network constraints cannot be resolved by the utilization of traditional network assets.

Thus, a utility DERMS, through the provision of ANM features, combines utilization of traditional network assets, flexible connections, and flexible services to relieve network constraints in the most economical way. Through integration with the flexibility markets, utility DERMSs receive available bids for flexibility services in the distribution grid. The available bids are received in the form of merit order lists containing customers/DERs with the offered flexibility, capacity, and price. To enable competition for flexible services, utility DERMSs assess the network conditions in near-real time (several hours ahead), detecting the constrained network area and the required capacity. This information is transparently shared on flexible markets with all interested stakeholders, in order to enable their registration and preparation to offer flexibility services in the time, capacity, and location where these services would be needed. In this way, utility DERMSs significantly help in enabling energy democratization, and provide the opportunity to all interested parties to offer their service, while at the same time providing assurance to the DSOs that the distribution grid will always operate within the technical boundaries.

5. Utility DERMS Benefits

To clearly demonstrate the need for electric utilities to implement the utility DERMS solution, several general use-cases that have already been either tested in the simulation environment or during the industrial field projects will be presented:

- Highly accurate real-time and forecasted situational awareness of large amounts of dispersed DERs;
- Utility DERMSs provide highly accurate situational awareness of real-time conditions in the grid—voltages, current and power flows, congestion, etc.—through SCADA and advanced metering infrastructure (AMI) systems, as well as through their advanced algorithms for grid monitoring. Moreover, through sophisticated load and DER forecast algorithms, accurate predictions of future grid conditions are estimated. However, with the emergence of high penetration of behind-the-meter DERs and flexible loads, frequently not connected to SCADA or AMI systems, their conditions have traditionally been estimated using state estimation or other advanced applications. Nevertheless, DER aggregators enable near-real-time measurements of small-scale DERs, not connected to SCADA or AMI systems, as well as accurate forecasted behavior of DER groups composed of these small DERs. With these data being constantly imported from DER aggregators, utility DERMSs increase the accuracy of their real-time situational awareness and expand it to the grid-edge devices, as well as increasing the accuracy of their predicted grid conditions by enhancing their quality with the forecast obtained for DER groups managed by DER aggregators;
- Adaptive relay protection on feeders with high DER penetration;
- As the penetration of DERs in distribution feeders is constantly increasing, traditional relay protection settings and coordination methods are becoming inapplicable. Moreover, most emerging DERs have completely different fault currents relative to traditional generators, so the protection devices in their presence need to be set and coordinated with high precision. Therefore, new relay protection methods, adaptable to the highly dynamic conditions caused by emerging DERs, are essential for the safe and secure operation of distribution systems with high penetration of DERs;
- This is where the utility DERMS solution provides tremendous benefits to distribution utilities. With their adaptive relay protection module and a complete awareness of the behavior and status of all DERs within the system, utility DERMSs adapt relay settings in real time, and accordingly secure an accurate setting and coordination of the protective devices at all times and for different network conditions—highly variable because of uncertain and volatile DER production and status. High penetration of renewable DERs must be accompanied by the proper tools for adaptive relay protection, and as the utility DERMS provides both the real-time measurements from the field as well as an awareness of the entire grid through an accurate network model, only such a solution can be a proper platform for sophisticated adaptive relay protection methods that ensure the protection of the entire grid at all times;
- Utilizing flexible services to manage constraints in the distribution network;
- In today's distribution systems, where the number of DERs is progressively increasing, the utility is faced with a number of challenges introduced by DERs, such as high voltages, reverse power flow, and overloading conditions that cannot be resolved in traditional ways by utilizing traditional network assets (e.g., switches, tap changers, capacitors). Therefore, having the opportunity to utilize flexible services enhances the capability for utility networks to operate within technical constraints [26,27];
- Through ANM, the utility DERMS controls and manages traditional network assets, along with flexible services provided by DERs and DER aggregators, in a cost-effective way. Considering traditional network assets as zero-cost resources, the active network management will always try to resolve network constraints using network assets. However, when traditional assets do not provide the required benefit in constraint resolution, the ANM will utilize flexibility services with respect to their offered capacity and the price on the flexibility market so as to provide the least expensive solution to

the network constraint for all participating parties. Utilization of flexible services may be dispatched in real time or scheduled for anticipated time periods when constraints would otherwise occur;

- Proactive mitigation of look-ahead constraint violations;
- Through state forecast and look-ahead constraint management applications, utility DERMSs predict and proactively mitigate potential grid violations with cutting-edge precision. During one of the trial cases, the utility DERMS' state forecast predicted a reverse flow issue on a supply transformer in a tested substation. A look-ahead alarm was issued within the utility DERMS, which triggered look-ahead constraint management in a closed loop. Look-ahead constraint management detected a DER group consisting of behind-the-meter energy storage and controlled by a DER aggregator, and calculated that increasing their charging power during the critical period would mitigate the reverse flow issue. The utility DERMS consequently calculated and sent the appropriate schedule to the DER aggregator. The DER aggregator responded with a modified forecast for this DER group, which was considered in the utility DERMS' state forecast, informing the operator that the predicted reverse flow issue would be successfully avoided;
- Manage electric vehicle integration in the grid;
- The growing popularity of EVs introduces new loading challenges that did not exist in the era of traditional distribution systems [28]. Fast EV chargers can easily double the peaks of customers' demand. Moreover, it is difficult to firmly predict the exact periods of charging and, consequently, the periods of peak demand. Therefore, without proper observability and management of EVs, their integration into the distribution grids can be extremely challenging. Only if they are properly managed, with an exact awareness of the complete system and its correspondent constraints, can a high penetration of EVs be safely integrated;
- Through their advanced applications and communication capabilities, utility DERMSs can provide full awareness and controllability, essential for the secure integration of a high penetration of EVs. By exchanging data with EV aggregators in real time, utility DERMSs are always aware of the loading that they impose on the grid, as well as of their flexibility, which can be used in advanced applications for constraint management, grid optimization, and the most economic usage of these resources. Thus, having a centralized management solution will not only provide a safe and violation-free means of integrating a high penetration of EVs, but will also provide DSOs with a new flexible resource to optimize the dynamic behavior of the emerging grids.

6. A Numerical Illustration of the Value of the Utility DERMS for DSOs

In this section, one real-life example will be presented and elaborated. This example has already been tested within a real-life case study for the integration of the EcoStruxure DERMS (a state-of-the-art, commercially available utility DERMS solution) [21] and several DER aggregator providers. These tests were performed in a factory environment, but as they show very promising results, they are planned to be implemented in several industrial pilot projects in the coming year. The EcoStruxure DERMS is used as a solid example of the commercially available utility DERMS solutions, by which the authors' claims can be clearly presented to the readers of this article.

This test case was performed on a real-life feeder, presented in Figure 2 [29]. The feeder was modified from its original state as follows: All line sections are three-phase, with mutually equal series parameters (Z = 0.09 + j0.36); shunt impedances are neglected. Four DERs are located at buses 22, 28, 63, and 73. The DER in bus 22 is a solar plant of 1.5-MW peak power, whereas the DERs in busses 28, 63, and 73 are energy storage units with rated charging power of 0.5 MW each. Energy storage units can be charged/discharged with a maximum of 0.5 MW, for a maximum of 2 h. All four DERs, when exporting power at their maximum capacity, supply roughly 40% of the peak load, which is 7 MW. This makes this a perfect example of the emerging distribution feeder with high DER penetration.

A third-party DER aggregator aggregates all of the DERs, and has permission (through separate contracts with DER owners) to manipulate the schedules of individual DERs within their contractual limits. Bus 0 is the root of the feeder, via which it is connected to the supply substation.



Figure 2. Real-life 186-bus feeder.

At the beginning of the observed period, the loading was at nearly 100% (6.8 MW), consisting of normal load and energy storage, which were charging as per their normal schedules. Solar PV was producing at its full capacity; thus, roughly 5.3 MW was coming from the supply substation. The real-time state of the feeder was constantly observed through the EcoStruxure DERMS, with the information regarding third-party DERs constantly being imported from the DER aggregator (Figure 3).



Figure 3. Distribution network state observed through the utility DERMS.

Suddenly, as clouds appeared, the production from the solar PV was lost (this was simulated through the network simulator tool within the EcoStruxure DERMS), which caused all of the required power to be imported from the supply substation. This consequently caused overload violation at the feeder head (at the section between buses 1 and 2). The overload was immediately detected by the EcoStruxure DERMS, and appeared in the form of a section blinking and the overload alarm (Figure 4).



Figure 4. Overload detected through the utility DERMS.

This violation consequently triggered the EcoStruxure DERMS' constraint management application. Among its resources for constraint resolution, the DERMS detected a DER group managed by a third-party DER aggregator, consisting of batteries and a solar PV (a symbol consisted of a solar PV and a battery, depicted beside the feeder head in Figure 4). Constraint management automatically calculated that this DER group could provide enough flexibility to mitigate the overload condition, by switching one of the batteries from charging to discharging. The calculated command was consequently automatically sent to the DER aggregator to change the schedule of the battery (Figure 5).



Figure 5. Overload resolution through the EcoStruxure DERMS.

Finally, the third-party DER aggregator dispatched commands to its individual DER assets to increase production and alleviate congestion (one battery changed from charging to discharging; for other DERs, schedules continued as they were). Thus, the excess load was provided with the battery and the overloaded section on the feeder head was unburdened. Through the real-time measurements, the EcoStruxure DERMS confirmed that the overload issue had been successfully mitigated, and the alarm disappeared, informing the operator that the violation had been successfully solved (Figure 6).



Figure 6. Overload successfully resolved through the EcoStruxure DERMS.

7. Discussion

The presented example is just one of many examples of how utility DERMSs can enable full ANM functionality to DSOs, but it clearly shows the advantages that utility DERMSs may provide—namely, with the inevitable and ever-increasing DER penetration around the globe, DSOs will either find themselves in a world of troubles if they stand still and wait for the emerging conditions unprepared, or they will accept the changes and move forward, adapting their processes to the new conditions. The only way to do the latter is to make themselves familiar with novel and intelligent centralized software solutions that will provide them with a complete awareness of the grid conditions 24/7, and an ability to react in real time, prevent the issues, and optimize the grid behavior by utilizing the flexibility of DERs and other dynamic assets in a centralized and intelligent fashion. Utility DERMSs are such a solution, providing a full spectrum of ANM functionalities integrated in a single package.

It is also worth mentioning that the traditional means of solving congestion issues such as the one presented above would be to replace the cables and other equipment with stronger ones, or even to build a new substation and share the load, in some more critical cases. However, this traditional method would require significant monetary investment, as well as a long period for approval by the relevant regulatory bodies. Moreover, an increasing number of regulators around the globe is starting to require utilities operators to actively manage the grid constraints by using the available flexibility of existing DERs, instead of investing in building and strengthening the grid assets. In other words, the non-wires alternatives of solving the issues in the grid are becoming mandatory. Thus, DSOs and grid engineers must make themselves familiar with the novel tools for active network management, such as utility DERMS solutions, in order to keep up with the regulations and enable massive DER integration in a safe and secure manner. This paper aimed to introduce this novel but highly important concept, and to offer the authors' view of the required near-future developments in the area of active network management of emerging distribution grids.

Finally, it is important to note that decentralized solutions for DER management such as DER aggregators, DER market providers, microgrid controllers, etc.—are also very important assets on the sustainable energy transition journey. These solutions are aimed at different stakeholders and for achieving different goals relative to the utility DERMS (see Table 1), but are nevertheless compatible with centralized utility DERMS solutions, as they provide grid-edge awareness, aggregated flexibility, and market participation of the aggregated DERs, which certainly complements and improves utility DERMSs' capabilities. A good example is a mutual project conducted between Schneider Electric, Argonne National Laboratory, Schweitzer Engineering Laboratories (SEL), The US Department of Energy, and the Philadelphia Electric Company (PECO) on the integration of a utility DERMS and a microgrid controller for utilization of the microgrid DERs' flexibility for constraint management and technical optimization of the utility feeders [30]. However, as most of these solutions are new, and have not yet been fully tested in the field, optimal coordination, communication, and integration protocols, as well as a clear distinction between the roles and responsibilities of centralized and decentralized DER management solutions, are all still open issues that are currently being worked on. These will certainly be among the future directions for the authors' research.

8. Conclusions

With a rapidly increasing penetration of DERs around the globe, unequivocally demanded by governing bodies, DSOs must adapt to emerging conditions and be able to successfully ride through these changes. Moreover, an increase in the proliferation of small-scale, behind-the-meter assets is swiftly changing a traditionally passive demand into a highly active and dispersed set of very dynamic prosumers. To cope with certain challenges of tomorrow's distribution systems imposed by new and unprecedented DER technologies, DSOs must be able to intelligently and safely manage and control a wide set of DERs, from grid-edge behind-the-meter devices, all the way to large-scale units, connected to medium-voltage grids. The authors' focus in this paper was on explaining how a state-of-the-art utility DERMS solution can provide DSOs with the required capabilities to safely overcome all of the coming challenges and, furthermore, to successfully transform challenges imposed by DERs into operational and monetary benefits for both DSOs and end customers.

The future research directions in this area, in addition to those discussed in the previous section, will be centered around developing and introducing novel methodologies for the distribution grid planning engineers, which will enable them to accommodate high penetration of renewable, electronically coupled DERs. This area encompasses the hosting capacity functionalities, which will enable the planning departments to analyze the available capacity of the existing grids to host new DERs, as well as algorithms to predict the influence of the planned resources on the grid conditions, and the methodologies to plan their schedules in an optimal way, in order to avoid congestion in the most critical periods.

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