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Distributed energy resource management systems—DERMS: State of the art and how to move forward

Luka Strezoski[1,2]

[1]Department for Power, Electronics and Telecommunications, Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia

[2]Schneider Electric, Novi Sad, Serbia

Correspondence
Luka Strezoski, Department for Power, Electronics and Telecommunications, Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovica 6, Novi Sad 21000, Serbia.
Email: lukastrezoski@uns.ac.rs

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Abstract

Due to an ever-increasing rise in proliferation of distributed energy resources (DERs), the paradigm of passive electrical distribution networks is shifting toward active distribution systems. This new environment introduces a plethora of challenges that cannot be managed by traditional tools, whose utilization could compromise the reliability and efficient operation of distribution feeders. This article systematically reviews state of the art in different DERs management software solutions available today. Additionally, it establishes distinguished roles and responsibilities of different levels of hierarchy in distinct solutions that are all commonly called DERs management systems—DERMS (e.g., fully centralized versus fully decentralized DER management solutions). Lastly, it offers a viewpoint on the directions that hold potential for the power system community and industry to explore for further developments of more robust and intelligent DERMS, to successfully enable efficient transition into a new era of clean and sustainable power systems, encompassing active and dynamically changing distribution circuits.

This article is categorized under:

Climate and Environment > Net Zero Planning and Decarbonization
Energy and Power Systems > Distributed Generation
Energy and Power Systems > Energy Management

KEYWORDS

active network management, DER aggregation, DERMS, distributed energy resource, non wire alternatives

1 | INTRODUCTION

The paradigm of passive distribution networks, with a sole aim of transporting energy from transmission grid to the end-customers is rapidly fading away (Chowdhury & Crossley, 2009; Hidalgo et al., 2010; Lund et al., 2019; Sajadi et al., 2019). With a significant rise in proliferation of distributed energy resources (DERs) around the globe, we are witnessing a shift of this paradigm as we enter the world of highly complex distribution systems. This transformation is driven by important initiatives for renewable energy integration, electrification of transport, and clean energy goals set by governments all over the world. As renewable energy and electric vehicles (EVs) are integrated into the distribution grids, a new era of complex, active, and dynamically changing distribution systems is inevitable (Hodge et al., 2020; Huang et al., 2019; IRENA, 2015; Kroposki et al., 2017; Lund et al., 2019).

Active distribution grid, in a context of this article, means that there are generators that are producing power inside the distribution grid. Thus, it is an active system, contrary to passive distribution networks that were used solely to transport the energy from supply substations to the end-customers. Dynamically changing distribution grid, in a context of this article, means that its conditions are changing in real-time. This can be caused by EVs, volatile nature of renewable DERs, and so on. Thus, distribution grid can be active (e.g., there are traditional generators connected to the distribution level), but not dynamic (there are no dynamic resources—intermittent sources, EVs, etc.). Active and dynamically changing distribution grid is the most complex case, when there are all types of DERs connected to the distribution level, that cause a dynamically changing environment in real-time. This emerging class of distribution circuits is the main subject of this article.

As DERs are mainly based on novel technologies to support solar and wind energy, electrical energy storage systems, EV chargers, as well as aggregated DERs in forms of microgrids, virtual power plants (VPPs), and demand response programs (DR), DERs play a crucial role in the renewable energy transition. Thus, as numerous research reports clearly state, it is to be expected that the proliferation of DERs will continue to significantly increase all over the globe (Guidehouse, 2019, 2020, 2021).

Naturally, integration of these novel technologies into traditionally passive distribution networks is followed by a plethora of challenges (Aguero et al., 2016; Aguero & Khodaei, 2018; Bravo et al., 2015; Martins & Borges, 2011; Mokryani et al., 2017; Mokryani et al., 2018; Reno et al., 2021; Singh et al., 2016; Strezoski et al., 2020). Challenges caused by an increasing integration of DERs range from planning and selecting the optimal locations for placement of new DERs (Martins & Borges, 2011; Mokryani et al., 2017; Mokryani et al., 2018), real time technical violations such as overload and reverse power flow problems caused by variable nature of renewable DERs, under/over voltages at the DERs' neighboring busses (Aguero et al., 2016; Aguero & Khodaei, 2018; Bravo et al., 2015) to malfunction and miscoordination of the protective systems caused by dynamically changing fault currents from DERs (Reno et al., 2021; Singh et al., 2016; Strezoski et al., 2020).

These challenges cause traditional procedures and techniques used by distribution network operators (DNOs) to be insufficient for an efficient management of emerging distribution systems. Moreover, grid expansions required to host new DER and EV integration cannot be planned and performed by using traditional procedures challenges (Martins & Borges, 2011; Mokryani et al., 2017; Mokryani et al., 2018). Thus, to provide a reliable transition into a new era of active and dynamically changing distribution systems, distribution control centers, and their personnel need new tools, procedures, and trainings that will allow them to properly plan, control, and manage such complex systems, that are inevitably arriving (Aguero et al., 2016; Aguero & Khodaei, 2018; Bravo et al., 2015).

To overcome these challenges and pave the way toward efficient energy transition, novel software solutions called Distributed Energy Resource Management Systems (DERMS) are emerging (EPRI, 2021a, 2021b; Faria, 2019; IEEE, 2021; Ilic et al., 2020; Petrovic et al., 2019; Rahman et al., 2021; Strezoski et al., 2022; Strezoski & Stefani, 2021; Strezoski, Stefani, et al., 2019; Strezoski, Vojnovic, et al., 2019; J. Wang, Chen, et al., 2015; Q. Wang, Zhang, et al., 2015; Wang et al., 2020). DERMS solutions aim to offer distribution system operators (DSOs), grid planners and engineers, as well as end-customers and prosumers an opportunity to enter a new era of active and dynamic distribution systems, and even gain both technical and monetary benefits from this transition.

Nonetheless, DERMS solutions are still emerging and most of them are currently quite immature, which is the reason why DSOs are often reluctant with going forward in deploying DERMS directly into their control centers. Moreover, even a term DERMS itself is novel, so it can often refer to very different hierarchical levels of software solutions, aimed for different stakeholders and for satisfying completely different goals with using DERs (Petrovic et al., 2019; Strezoski & Stefani, 2021). On one end of the spectrum, there are decentralized DER management solutions aiming to provide basic, but highly important features such as aggregation of behind-the-meter DERs, and participation of DERs and prosumers in DR and energy efficiency (EE) programs. These solutions can (and mostly are) indirectly used by DSOs, but are designed for direct utilization by independent aggregators, market operators, and other third party participants (Kerscher & Arboleya, 2022; Mousavi & Meng, 2021; Yi et al., 2021). On the other end, there are fully centralized solutions, aimed for direct utilization by DSOs, to aid them in overcoming challenges imposed by DERs onto distribution grids and their assets. The confusing part is that because of the novelty of the term DERMS, most of these, obviously completely different software solutions for DER management, are all simply called DERMS.

To overcome the confusion between different DER management solutions, in this article they will be systematically distinguished, and each of them will be properly termed with their current state of the art reviewed. Moreover, the complementary natures of these different solutions will be explored, and it will be shown how an optimal integration between centralized and decentralized DER management solutions may provide distribution utilities with a wide set of tools to propel them toward efficient management of emerging distribution grids.

Thus, the goals of this article are set forth as follows: (1) To systematically review state of the art in different DER management solutions available today; (2) To distinguish roles and responsibilities of different levels of hierarchy in distinct solutions that are all commonly called DERMS (i.e., fully centralized versus fully decentralized DER management solutions); and (3) To offer this author's view on the directions that the Power System community and industry should take in DERMS development in order to successfully enable efficient transition into a new era of clean and sustainable power systems, with complex and dynamically changing distribution grids.

The remainder of this article is organized as follows. In Section 2, the historical evolution of DER management solutions is discussed. In Section 3, different hierarchical levels of existing DER management solutions are discussed and systematically distinguished. In Section 4, centralized enterprise solutions for DER management are introduced, and their current state of the art is discussed. In Section 5, different decentralized solutions for DER aggregation and market participation are discussed and their state of the art is reviewed. In Section 6, the complementary nature of centralized and decentralized DER management solutions are explored, along with the benefits that their proper integration may provide to DSOs. After Section 6, this author's perspective regarding answering the question "What is DERMS?," and which terminology should be used for each specific DER management software solution should be clear to the readers. Finally, Section 7 contains this author's view on the directions that the Power System community and industry should take in further DERMS development to enable efficient transition toward active and dynamic distribution grids. The article is concluded in Section 8.

2 | THE HISTORICAL EVOLUTION OF DER MANAGEMENT SOFTWARE SOLUTIONS

All DER management solutions have historically evolved from two different sources: (i) Centralized distribution grid management platforms and (ii) Decentralized customer management solutions. This section discusses the evolution of DER management software solutions.

Centralized solutions for management of emerging distribution grids have evolved as a response to integration of DERs in the last two decades, and inability of traditional tools that DNOs have been using, to cope with the challenges that DERs impose to distribution grid assets. It has become challenging to plan the integration of high amounts of DERs by using traditional tools, as the influence of DERs on technical constraints of the grid assets could not be properly analyzed without appropriate models and techniques (Martins & Borges, 2011; Mokryani et al., 2017; Mokryani et al., 2018). Moreover, management of emerging distribution grids, in a new environment with high amounts of DERs and consequent multi-directional power flows, high chance of reverse power flows, dynamic voltage fluctuations, and so on, could not be efficiently performed with traditional tools and techniques used by DNOs for the past several decades (Aguero et al., 2016; Aguero & Khodaei, 2018; Bravo et al., 2015). This core transformation of the structure of traditionally passive distribution grids called for another core transformation: DNOs have been required to take a much more involved role and to be capable of managing distribution grids inside technical constraint boundaries in real time, 24/7 (Boyd, 2017; Burger et al., 2019; Li & Kong, 2018; Strezoski et al., 2022; Strezoski & Stefani, 2021).

In other words, as passive distribution networks evolved toward active and dynamic distribution systems, DNOs have been required to evolve into much more active players, called DSOs (Boyd, 2017; Burger et al., 2019; Li & Kong, 2018). To enable this transition, vendors that have been developing traditional supervisory, control, and data acquisition (SCADA) and distribution management system (DMS) tools, have started to expand their solutions and to develop novel software packages that would add proper tools to assist DSOs in integrating and managing high amounts of DERs in a centralized fashion. Their aim has been to consider complete grid with all its assets and to have the ability to analyze and to properly react to the influence that DERs impose to the grid assets (ABB, 2020; General Electric, 2021; Open Systems International, 2020; Schneider Electric, 2019; Siemens, 2021) These centralized and grid-aware, enterprise software solutions, which aimed to enable DSOs and grid engineers a centralized way of managing distribution grids with high penetration of DERs, have initially been called simply DERMS solutions.

The second direction from which DER management solutions started evolving, came from the side of end-customers. Traditionally, DR and EE programs used incentives (mostly monetary) to encourage end-customers to reduce their demand in critical periods and to help operators in managing the balance between generation and demand

(Albadi & El-Saadany, 2008; Medved et al., 2018; Spees & Lave, 2007). These programs would aggregate numerous end-customers and use their aggregated power for peak-shaving, demand shifting, and other services requested by the authorities (EDSO, 2014; Goldman, 2010; Ponnaganti et al., 2018). This proved to be a good and satisfactory practice for all the parties involved, as the customers would earn by reducing their demand in periods that they decide will suit their needs, whereas electric utilities would avoid some more drastic measures such as load shedding, or on-boarding of reserve power plants. However, with the emergence of high penetration of DERs, especially small-scale ones such as rooftop PVs, small batteries at the customer sites, as well as EV chargers, new challenges as well as new opportunities emerged. These small-scale, but highly dynamic resources are causing new issues at their locations such as voltage fluctuations, reverse power flows, and dynamically changing fault currents, but they may also provide a much-needed flexibility and offer new opportunities for more efficient demand management and energy savings schemes (Rahimi & Ipakchi, 2010; Tulabing et al., 2016; Tuohy et al., 2014; J. Wang, Chen, et al., 2015; Q. Wang, Zhang, et al., 2015). As the emerging environment introduces new challenges at the customer sites, which cannot be solved by simple DR programs, as well as with a vision of regulating bodies to encourage utilization of the flexibility offered by aggregated behind-the-meter DERs, traditional DR, and EE technologies have started to expand and enable DER aggregation, DER participation in DR, and "reverse DR" programs (instead of just reducing or shifting demand of consumers, an ability to increase demand when needed), as well as an ability for behind-the-meter DERs to participate in electricity markets and monetarize their flexibility (Ault, 2020; Autogrid, 2020; Feldman & Callaway, 2016; Mprest, 2021). Paradoxically, these fully decentralized solutions for DER aggregation and basic DER management have also initially been called simply DERMS.

In Figure 1, the historical evolution of DER management solutions from two distinct sources is conceptually presented.

The discussion above suggests that due to novelty of DER management software, various completely different solutions with distinct roles and responsibilities, are all frequently termed DERMS. This often leads to a confusion among the key stakeholders interested in deploying DERMS, as they might be unsure if the solution picked will meet their specific needs. This ill-defined distinction serves as the motivation for the next sections where a clear distinction will be made between different hierarchical levels of DER management solutions, along with the discussion about the roles and responsibilities of each of these technological solutions.

3 | DIFFERENT LEVELS OF DERMS HIERARCHY

As a first step toward distinguishing between different levels of hierarchy among current DER management software solutions, Table 1 is provided (Strezoski & Stefani, 2021). In this table, first key stakeholders interested in deploying DER management software are sorted out. Next, goals that each of these entities desires to achieve with DER management software are explained. Finally, the hierarchical structure of the software itself, required to achieve the desired goal, is marked besides each of the listed solutions.

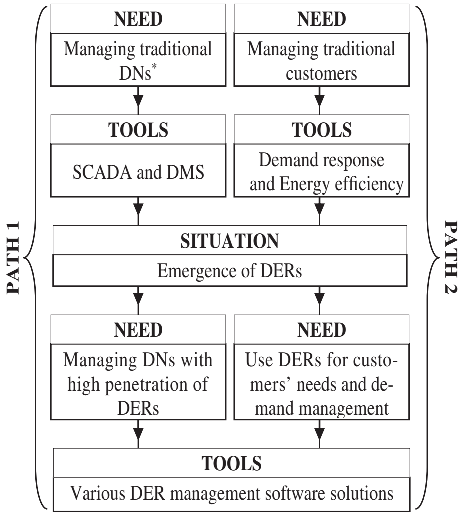

FIGURE 1 The historical evolution of distributed energy resource (DER) management solutions

TABLE 1 Different distributed energy resource (DER) management solutions, their goals, and their hierarchical structure

Stakeholder	Goal	Architecture
Distribution system operator, Planning and innovation departments in distribution utilities	Relieve congestions and voltage violations, solve reverse power flow problems, defer network reinforcement, enhance distribution grid hosting capability, optimization of existing and new assets, secure grid edge stability, and so on.	Centralized; aware of the accurate network model
Market participants and electricity 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; not aware of the accurate network model
Prosumers, microgrid operators, DER aggregators	Aggregate DERs for: local energy management, including microgrids, to optimize costs (energy charges), integrate DGs, and improve resiliency	Decentralized and local; not aware of the accurate network model

It is important to note that besides DER management solutions listed in Table 1, local controllers, such as home energy management systems, also should be represented at the "lowest" hierarchical level of DER management tools, on the opposite side of the spectrum from a Utility DERMS. Indeed, considering the status quo where the penetration of behind-the-meter DERs still has not reached critical and problematic levels in most parts of the world, these small-scale local controllers can opt to not be concerned with rest of the grid and operate entirely on their own. However, with increasing trend of deployment of behind-the-meter DER penetration, the lax view on it will most probably become inadequate in near future (as in some places like Southern California, the distribution system is nearing that point—for instance, the problem of California duck curve). Therefore, to complete this structural presentation, a communication channel between these local controllers with either directly Utility DERMS or through aggregators will be required, at least to provide situational awareness to operators. Depending on regulations of a specific country, operators may also be able to use the flexibility of these resources for their needs, by participating on the energy market, and this process would also be handled through aggregators and Local Electricity Market Operators, of which more details will be elaborated in the later sections of this article.

Table 1 indicates that throughout daily operation involving DERs, a number of stakeholders are pursuing various and at times conflicting interests, and thus need different DER management solutions. Moreover, to satisfy the specific needs of stakeholders, DER management solutions may be fully centralized enterprise systems deployed at the utilities' control centers, or on the other hand, decentralized solutions deployed closely to the DERs and end-customers. Thus, besides the fact that these solutions differ in the functionalities that they need to provide, they also differ in the core structure of how they should be developed and deployed.

It is important to note here that both centralized and decentralized DER management solutions are essential to enable an efficient energy transition toward sustainable and clean power systems. Nonetheless, a fact that all these solutions are often simply called DERMS could be confusing and lead to misunderstanding among the key stakeholders (i.e., DSOs, microgrid operators, market participants, etc.), in regards to which of the currently available solutions is the most suitable for their specific needs (Strezoski et al., 2022). Thus, in the following sections, a clear distinction between main DER management solutions currently available on the market will be discussed, and state of the art of each of these solutions will be reviewed.

4 | CENTRALIZED DER MANAGEMENT SOLUTIONS: STATE OF THE ART

As discussed in previous sections, centralized DER management solutions evolved as a response to inability of legacy control centers (mainly equipped with SCADA and/or DMS) to cope with DERs, and challenges that their integration imposes to the distribution grid assets and operation of emerging distribution systems—Path 1 in Figure 1. To provide a proper awareness of the entire grid with all its assets, as well as of the impact that DERs have on the grid, these centralized software solutions need to be grid-aware—they need to provide accurate network model with all the grid assets considered in the model (Anaya, 2021; Schneider Electric, 2019; Siemens, 2021; Strezoski et al., 2022). Moreover, in addition to the traditional model, they need to provide an ability to represent all DERs, with every characteristic properly modeled within an appropriate representation that corresponds to the timescale of interest. These include rated and maximum powers, number of phases (three-phase or a single-phase DER), rated currents and voltages, internal impedance values, contractual obligations, points of common couplings (PCCs), network and circuit topologies, and the method used for connection to the grid, but also in the case of inverter based DERs (IBDERs), functionalities that inverters may provide (e.g., grid-forming vs. grid-following, frequency response, voltage support, ride-through, etc.) (ABB, 2020; General Electric, 2021; Schneider Electric, 2019; Siemens, 2021; Strezoski et al., 2022; Strezoski & Stefani, 2021). Further, and on top of the accurate network model, to provide awareness of the precise grid conditions in real time, these software solutions must deploy state of the art power flow and state estimation algorithms that are constantly supplied by real-time SCADA and Advanced Metering Infrastructure (AMI) measurements, load and generation forecasts, real-time topology, and as-operated switching state from the field, as well as planned schedules from DERs based on their market participation. Finally, above the core applications for network analysis, these solutions need to contain advanced applications for control, optimization, and protection of distribution grids with high amount of DERs dispersed all over the grid (Strezoski et al., 2022; Strezoski & Stefani, 2021).

Thus, centralized DER management solutions, aimed to aid DSOs in overcoming challenges that high amount of DERs impose to the grid assets and in overall management of emerging grids, shall be completely grid-aware enterprise solutions, deployed at the DSO's control center [42-46]. Therefore, a proper terminology that should be used when speaking about such solutions is "Utility DERMS" (henceforth used in this article) or "Grid DERMS."

Most of the major vendors agree that a Utility DERMS shall contain a comprehensive real-time module for management of emerging distribution grids with high penetration of DERs (ABB, 2020; General Electric, 2021; Open Systems International, 2020; Schneider Electric, 2019; Siemens, 2021), as well as computational efficiency to handle high rate of data input and networks at scale. However, some of the more advanced Utility DERMS solutions contain a planning module (which are slower in computational processing), as well as a look-ahead module (also slower in computational processing), besides the real time functions (which are the fastest in computational processing) (Schneider Electric, 2019; Strezoski et al., 2022). It is this author's belief that a Utility DERMS shall contain all three modules with enhanced computational capability (both algorithmically and computational architecture—including the choice of computing methods ranging from cloud to edge computing to cope with constraints that data volume, algorithmic complexity, and communication bandwidth impose), to be capable to properly mitigate all the DER-imposed challenges. Thus, in the following, the main functionalities of these three modules of a Utility DERMS will be discussed, and the current state of the art from available literature as well as from major DERMS vendors will be reviewed.

A high-level depiction of the Utility DERMS solution is presented in Figure 2.

4.1 | Planning module of a Utility DERMS

As the integration of DERs completely changes the landscape of distribution grids, and influences all its processes, including technical and operational, regulatory, as well as business procedures, integration of high penetration of DERs needs to be properly planned, using specialized set of tools and procedures (Alarcon-Rodriguez et al., 2010; Carpinelli

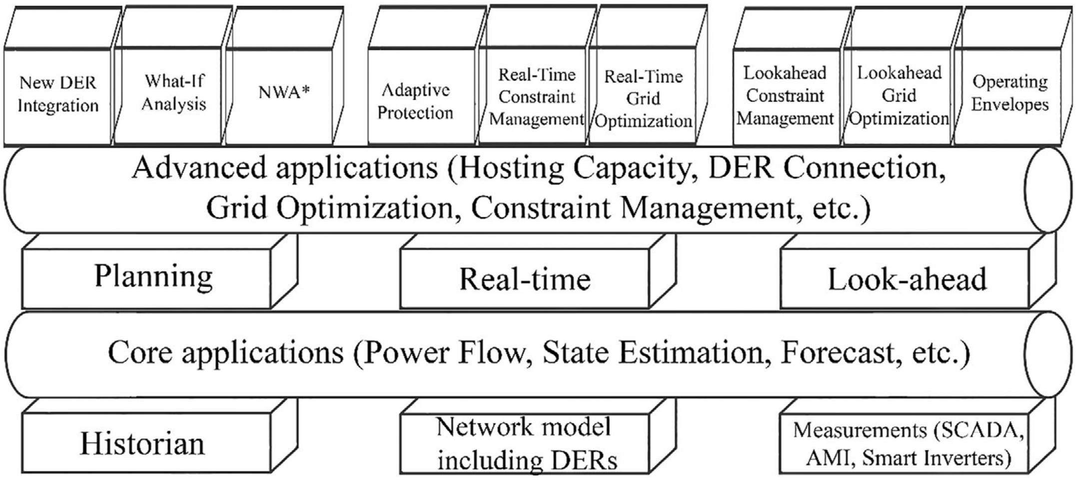

FIGURE 2 The Utility DERMS

et al., 2013; Sajadi et al., 2019; Strezoski & Stefani, 2021; Zain ul Abideen et al., 2020). Thus, a planning module that can provide a proper set of tools for grid engineers to perform comprehensive studies of adding new DERs to the existing grid should be an essential part of a Utility DERMS solution.

One of the most important aspects of a Utility DERMS planning module is the ability to investigate the hosting capacity of the existing grid and to construct Hosting Capacity Heat Maps (HCHMs). HCHMs are geographical maps of the grid, colored per the ability of the existing grid to host new DER (Ismael et al., 2019; Laaksonen et al., 2020; Smith & Rylander, 2014; Zain ul Abideen et al., 2020). Simply put, HCHMs are constructed within the planning module of a Utility DERMS, by performing load flow studies on an accurate network module, with incremental additions of new DER power into the network nodes using a wide range of probabilistic scenarios, upon the situation where the new increment would cause technical violations in the grid. They can be constructed by considering only critical cases, or more accurately, by simulating dynamically changing environment in distribution grids. When constructed, HCHMs can be placed on a DSO's web portal accessible to the potential customers and DER developers. Thus, an HCHM should be a starting point for a further and more comprehensive DER integration study.

When a specific DER connection request is received from a new customer or from a DER developer, or if a DSO is interested in building a new DER facility, further investigation is required. This is also performed within the planning module of a Utility DERMS, by using advanced planning applications developed for this purpose. In this step, the specific PCC for a new DER is analyzed, with its required rated power, technology type, and so on, and its influence on the rest of the grid is thoroughly analyzed. Obviously, a highly accurate network model and the devices planned for that facility as well as advanced applications are required for such a task. Once the initial study is performed, and if it is detected that a new DER would cause some violations in the grid, the planning department has several options. First, a study of traditional reinforcement of the grid assets can be performed (i.e., resizing the cables and other endangered assets). However, this traditional option can be costly and time-consuming, so a Utility DERMS should contain a set of tools to analyze the Non-Wire Alternative (NWA) ways of enabling new DER connection. This can be achieved in several ways. By offering to customers to sign so-called flexible contracts with DSOs, that would allow a DSO to curtail the excess power in critical periods (usually a fraction of a day or a month, or even a season), or by analyzing the options to use energy storage (including EVs), or available reverse DR capability, that can consume the excess power in critical periods, hosting capacity may be increased without the need for costly network reinforcements. A Utility DERMS should have all the required tools to enable such studies.

Finally, once the specific DER integration study is performed, and when all the options for increasing hosting capacity are exhausted, a Utility DERMS' planning module shall have the ability to conduct a multifaceted comparison for various options, based on policy-related, economical, technical, and reliability objectives for several years ahead for a better multi-vale assessment, and based on this comparison to enable planning departments to make the final decision regarding how to proceed with integrating new DERs. This process, on a high level, is presented in Figure 3.

4.2 | Real-time module of a Utility DERMS

Real-time module of a Utility DERMS is the main tool for monitoring, control, and active management of distribution grids with high penetration of DERs. As the penetration of DERs increases, observability and management of distribution grids becomes challenging without having a robust and reliable software tool for these purposes. In addition, to maximally utilize the flexibility of DERs and to use it to achieve overall benefits of all interested parties, a real-time Utility DERMS is inevitable (Ault, 2021; EPRI, 2021a, 2021b; SEPA, 2021).

As briefly discussed at the beginning of this section, a real-time module of a Utility DERMS is constantly fed by AMI measurements, SCADA data, measurements from sensors and smart inverters by which most of the DERs are connected to the grid, weather, load and generation forecasts, real-time topology, as-operated state of the grid, and so on (Strezoski et al., 2022). This comprehensive set of data is then sorted out and used in core applications that provide awareness and estimation of the real-time conditions in the grid. The main application that provides real-time status of distribution circuits is State Estimation, and its updated results are usually visible on a geographic view of the distribution grid, providing constant insight into current grid conditions to system operators. Using accurate network models, which includes the required data about DERs, State Estimation determines real-time conditions in the grid, improves unreliable measurements, and estimates the impact of DERs on distribution grid assets, with the highest precision. Besides providing visibility of the real time conditions, State Estimation should calculate possible violations, caused by

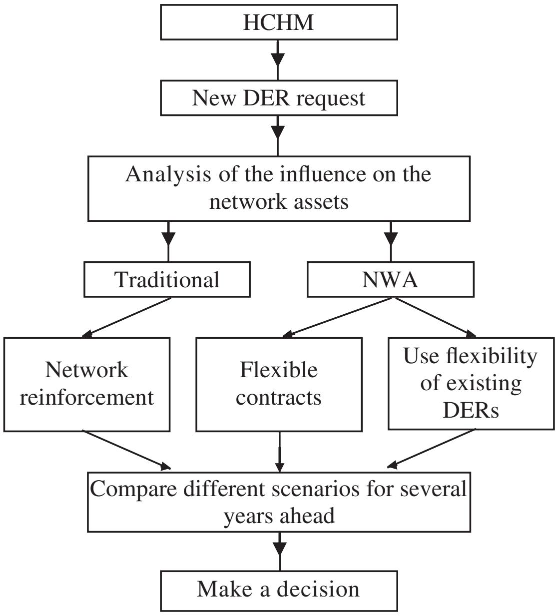

FIGURE 3 High-level overview of a distributed energy resource (DER) integration study

volatility of DERs, and in that way provide a starting point for further and more advanced applications, used for protection coordination, constraint management, and grid optimization.

To overcome challenges related to network limits that high penetration of DERs introduces—overloads, over/under voltage problems, reverse power flows, miscoordination of protection equipment, and so on, a Utility DERMS shall provide an ability for operators to react and solve these problems in real-time. Furthermore, to ensure that the grid is optimally managed, and that high amount of dispersed DERs work in coherence toward global optimum (depending on the goals of the specific DSO), Utility DERMS' real-time module shall contain a set of applications that manage a wide range of DERs in an efficient way.

At this point, one can raise the following question: should a Utility DERMS have a communication channel with every single DER (including the small-scale ones, connected to the low voltage—for example, rooftop PVs, individual EVs, household batteries, etc.), and is that even a feasible thing to expect in a situation where millions of new DERs are connected yearly? It should not be the job of the operator to control every single DER, from the DSO's control center, especially not the small-scale ones in a range of several kilowatts. However, to be able to avoid congestions and other problems caused by DERs, and to achieve an optimal operation of the entire grid, a form of control signal should be established. The answer to this dilemma has been found (by most vendors and their commercially available Utility DERMS solutions), as follows: Utility DERMS directly controls large-scale DERs through SCADA and internet protocols, whereas it indirectly controls small-scale DERs, through integration with third party software solutions aimed for DER aggregation (so-called DER Aggregators). Thus, a Utility DERMS uses DER Aggregators as its resources for constraint management and grid optimization, and should be understood as one layer above, in the hierarchical structure of DER management software solutions.

Utility DERMS, being completely aware of the accurate network model, uses traditional resources, such as load tap changers, capacitors, switches, and so on, in a mix with large-scale DERs, as well as DER Aggregators (which, as explained, aggregate large amount of small-scale DERs), to constantly run the distribution grid in a violation-free and optimal way (based on a preset optimization criteria). In this manner, the flexibility of DERs is maximally utilized, while the control centers are unburdened from having to communicate with large amount of dispersed DERs, as the combination of direct communication and computational processing is delegated to the hierarchically lower DER management software solutions. Advanced applications within the Utility DERMS will monitor the grid conditions 24/7, and upon any violation of the technical constraints or if the conditions deviate from the preset optimization criteria, a Utility DERMS attempts to solve the issue and return the grid inside technical boundaries by using traditional resources, such as switching and reconfiguration, load tap changers, capacitors, and so on, in addition to using the flexibility of DERs. The order of deploying resources (should traditional resources be used before DERs or vice-versa) depends on a specific DSO and the regulations in the specific country, but it should be configurable in a Utility DERMS, so that a DSO can set it in a desired way. Also, the cost of using traditional resources versus the prices on a flexibility market for using DERs, will play a major role in deciding which resources to use first.

Finally, a Utility DERMS may significantly help in improving asset utilization, by constantly running optimization applications, by tracking which resources are used in each optimization cycle, and then by constantly using all the resources that will help in achieving the preset optimization criteria, or return the distribution network conditions inside technical boundaries. Thus, with a Utility DERMS on disposal, operators and grid engineers will always be aware of the real-time conditions of an entire grid, with all the resources that could be used for constraint management and grid optimization, and by using DERMS' advanced applications, all the resources will be optimally utilized, each according to its share in contributing to the operator's goals and its previous utilization.

Figure 4 presents a high-level depiction of the real-time module of a Utility DERMS.

4.3 | Look-ahead module of a Utility DERMS

Due to dynamically changing conditions in the emerging distribution grids, caused by high amount of variable DERs and dynamic loads, DSOs need to be constantly aware of the forecasted conditions in the grid. This includes awareness of the network state (load flows, voltages, etc.), but also an ability to predict possible constraint violations, caused by a dynamic and volatile nature of DERs and EVs. Moreover, as the aggregated, small-scale DERs, as well as most of the large-scale DERs (especially energy storages), follow the preset schedules, a look-ahead module of a Utility DERMS should at least be able to estimate the impact of these scheduled outputs onto the grid assets (Belhomme et al., 2021; Chicco et al., 2020; Liu et al., 2021; Petrou et al., 2021). Thus, like a real-time module, a look-ahead module of a Utility DERMS shall contain State Estimation application but based on the forecasted inputs (load and generation profiles, weather forecasts, scheduled operation of DERs and DER groups, etc.).

Further, a look-ahead module shall at least be equipped with tools to detect critical schedules of DERs and DER groups (the ones that will cause constraint violations in the predicted future periods) and shall be able to propose their modifications to avoid violations. In other words, a Utility DERMS should be able to ingest and re-calculate the operating envelopes from DERs and DER Aggregators, based on its ability to analyze the influence of their scheduled operation on the network assets (Belhomme et al., 2021; Chicco et al., 2020; Liu et al., 2021; Petrou et al., 2020; Petrou et al., 2021; Riaz & Mancarella, 2021). Operating envelopes are defined by limits in which a scheduled production/consumption of a third party aggregator or a large DER needs to operate, that are calculated based on the predicted

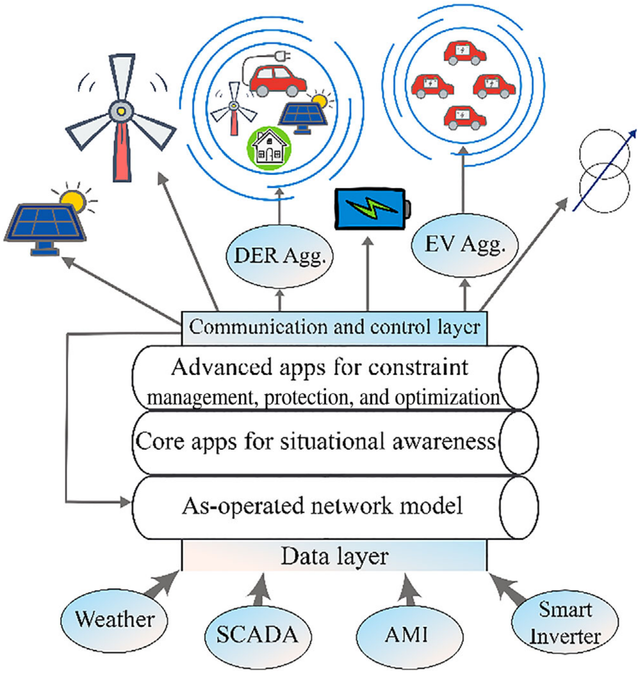

FIGURE 4 High-level representation of the real-time module of a Utility DERMS

conditions in the grid, to ensure that no technical violations are caused by the scheduled operation of these resources. This is the crucial ability that third party aggregators lack, because of their unawareness of the grid conditions.

This process is depicted in Figure 5.

Finally, most advanced Utility DERMS solutions, contain a so-called Look-ahead Constraint Management (LACM) sub-module (Strezoski & Stefani, 2021). The LACM is designed to be fed by core applications for look-ahead awareness and to be able to automatically detect possible violations in future periods, to be able to estimate the available flexibility of DERs and DER groups that can contribute to solving the violations, and finally to be able to automatically communicate with the resources (DERs and/or DER Aggregators) to use their flexibility to proactively solve the predicted violations before they take place. Most of the available LACM solutions are still in their infancy—within trial periods on pilot projects (mostly limited to small parts of the grids—i.e., one substation), but their results are promising (ARENA, 2020; ARENA, 2021a, 2021b). Recent advances in machine learning and artificial intelligence offer a great promise in advancing this realm and could be explored.

In this section, centralized DER management solutions were discussed. Next section continues with further discussion of the roles and responsibilities expected from decentralized DER management solutions.

5 | DECENTRALIZED DER MANAGEMENT SOLUTIONS: STATE OF THE ART

As Table 1 laid out, decentralized DER management solutions can be roughly divided into the following three categories: (a) DER Aggregators (VPPs and DR providers included); (b) Local Electricity Market Operators; and (c) Microgrid Controllers. Even though each of these three categories yield distinctive characteristics, there exist considerable overlaps in their roles and responsibilities, as explained in this section.

5.1 | DER aggregators

As already discussed in the previous sections, besides being connected to the medium voltage (MV) level, high amounts of DERs and dispatchable loads are being connected daily to the low voltage (LV) level and are dispersed across the LV circuits. These can be rooftop solar PVs, EVs and EV chargers, household batteries, air conditioning (AC) devices, and so on. When the local/regional regulation allows and these resources become fully dispatchable in real-time, all of them can provide some flexibility by altering their usage of power. However, as their rated powers are generally in a range of several kilowatts, individually they do not possess a leverage to negotiate and offer their services to DSOs, nor it can be expected from DSOs to have communication channels with every single DER

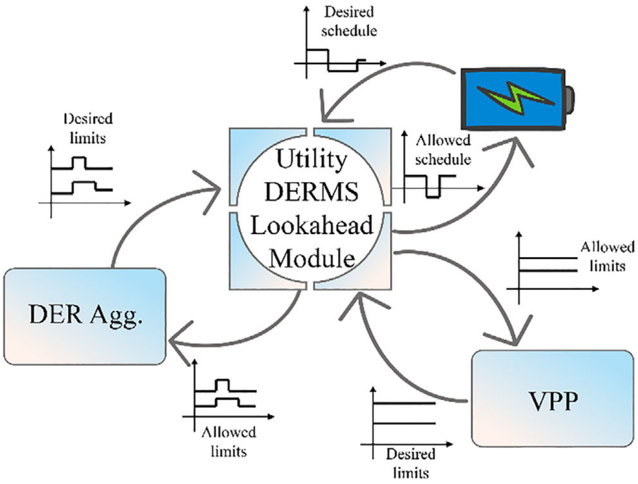

FIGURE 5 Communication of a Utility DERMS with distributed energy resources (DERs) and third party distributed energy resource (DER) aggregators

connected to the LV level, as discussed in the previous section of this article. However, the aggregated flexibility of large amounts of these DERs may be highly considerable and may present an asset to be used for various tasks, that include balancing voltage and power imbalance at the distribution level, dynamically managing technical constraint violations by using aggregated DER flexibility for NWA and for reliability increase, but also for frequency regulation as well as balancing supply and demand of electric power (ARENA, 2020, 2021a, 2021b; Belhomme et al., 2021; Chicco et al., 2020; Liu et al., 2021; Petrou et al., 2020; Petrou et al., 2021; Riaz & Mancarella, 2021). This is where DER Aggregators come into play, as their main aim is to communicate with and aggregate small, usually behind-the-meter DERs into DER groups, and then use their aggregated flexibility and provide various customer-related and ancillary services to DSOs, or even directly to the TSO (ARENA, 2020, 2021a, 2021b; Birk et al., 2017; Earley, 2020; Gerard et al., 2016; Givisiez et al., 2020; IRENA, 2019; Lund et al., 2019). Provisions that are directly offered by DER Aggregators include enabling aggregated DER power to participate in the electricity market (and consequently, to be used for balancing, frequency regulation or similar services), provision of DR and load shifting programs, peak load reduction, and other, mostly customer-related services, that can be used and coordinated for the benefits of the entire power system.

It should be noted that DER Aggregators do not have access to an accurate network model and are unaware of the grid level upstream and its technical constraints, such as transformer and lines' overloads, relay settings and coordination, voltage limits, or reverse power flow constraints (Liu et al., 2021; SEPA, 2021; Strezoski et al., 2022; Strezoski & Stefani, 2021). Thus, even though services provided by DER Aggregators are highly important as they increase the overall flexibility of distribution grids by enabling the usage of the flexibility of small-scale DERs, in most cases a DER Aggregator cannot be a sole DER management solution, as the schedules and dispatch of DERs provided by DER Aggregators alone may endanger grid assets, if they are not previously validated by the grid-aware enterprise solution, such as a Utility DERMS (SEPA, 2021; Strezoski & Stefani, 2021). Because of this, it is this author's belief that these highly important decentralized DER management solutions should not be called DERMS, but rather with a more appropriate term—DER Aggregators, a term that stands for their core role and for the responsibilities they should be able to provide.

5.2 | Local electricity market operators

As deployment of DERs can be expensive and as their integration may cause challenges that have already been thoroughly discussed throughout this article thus far, regulators, market operators and DER Aggregators have been starting to propose to harness their potential to provide market-based grid services that may lower their life-cycle cost (ARENA, 2020, 2021a, 2021b; Birk et al., 2017; Earley, 2020; Gerard et al., 2016; Givisiez et al., 2020; IRENA, 2019; Lund et al., 2019). However, regulation regarding DER market participation is still in its early infancy. Even for the countries where the regulation exists, their rules widely differ for different parts of the world (Bjarghov et al., 2021). Moreover, even though the market prices for electricity and ancillary services can be attractive, the sizes of individual DERs present a considerable barrier for them to enter the electricity market. In addition, almost all existing DERs are grid-following with no practical capability to provide the kind of support to the grid that qualifies for ancillary market product as an individual participant. Thus, this is where a tight integration between DER Aggregators and electricity market operators (and sometimes their considerable overlap), may come to its full potential. As stated in IRENA (2019) and IRENA (2020), to create a sizeable quantity of the flexible DERs' capacity to participate in electricity markets, aggregation of these resources needs to be allowed. As have been discussed in the previous subsection, aggregated DERs can provide essential services to DSOs (and even TSOs) and can participate in markets by selling electricity or ancillary services (IRENA, 2019).

However, as stated above, the first and fundamental step toward achieving this goal needs to be a regulatory reform, to provide incentive to untap the potential that DERs hold through the aggregation. A step closer as a significant milestone toward regulating DERs' involvement in electricity and ancillary services markets has been the Federal Energy Regulatory Commission's (FERC) Order No. 2222 that approves DER Aggregators to participate and be equal players on the North American wholesale electricity markets (Earley, 2020). Since then, a considerable effort has been put to organize separate entities that will enable a fair participation of DERs (through Aggregators) in wholesale markets. On the other hand, in Europe, and especially in Australia, there have already been numerous pilot projects that test the capabilities of DERs and DER Aggregators to participate in the electricity and ancillary services markets, and the results of these projects are promising (ARENA, 2020, 2021a, 2021b; Birk et al., 2017; Bjarghov et al., 2021; Earley, 2020;

Gerard et al., 2016; Givisiez et al., 2020; IRENA, 2019; Lund et al., 2019). FERC thus approves DER Aggregators to offer their services directly to the TSO on the wholesale market (but still requires validating their schedules against distribution-level technical constraints), European and Australian pilot projects mainly explore aggregated DER participation in the so-called local electricity markets, on a distribution level (Bjarghov et al., 2021). In either case, new entities that receive, sort, and communicate the bids and procurement auctions from DER Aggregators have becoming a reality all over the globe. These entities, for a distribution level and local electricity markets that are of interest in this article, are called Local Electricity Market Operators.

However, like DER Aggregators, these entities do not possess an accurate network model and are thus unaware of the impact that the services offered by DER Aggregators would have on the distribution grid assets. Therefore, they need to have established communication channels with a grid-aware Utility DERMS that will validate the schedules received from Local Electricity Market Operators, based on the grid conditions and constraints (ARENA, 2020, 2021a, 2021b). Several pilot projects have been testing this kind of integration among a Utility DERMS, DER Aggregators, and Local Electricity Market Operators, and the results promise a high success rate (ARENA, 2020, 2021a, 2021b). However, to deploy these solutions full-scale, on an entire distribution grid, or at least some larger parts of the grid, many of the questions of the regulatory responsibilities are yet to be cleared, such as who is responsible to set up contracts with DERs and DER Aggregators, who is able and allowed to dispatch individual DERs, should the local electricity market be centralized, decentralized, or hybrid, and finally, should DER Aggregators offer their services directly to the TSO, or rather on a local electricity market (Bjarghov et al., 2021).

5.3 | Microgrid controllers

As defined by the US Department of Energy, a microgrid is "A group of interconnected loads and DERs with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or islanded modes" (Parhizi et al., 2015). A Microgrid Controller is responsible for a proper operation of a microgrid, as well as for an efficient status switch—from grid-connected to islanded mode and vice-versa. Thus, like DER Aggregators, Microgrid Controllers aggregate DERs and loads, but unlike DER Aggregators, these collections of DERs and loads have clearly defined geographical boundaries and can serve as a micro power system of their own. Therefore, the first difference between DER Aggregators and Microgrid Controllers is a geographical distinction of individual resources. The second difference is that while DER Aggregators in most cases only offer their services to DSOs (and in some cases TSOs) to be used for their purposes, Microgrid Controllers additionally need to ensure that the microgrid itself is properly operated, which means that in the grid-connected mode they need to provide unit commitment, economic dispatch, and other services for operating their resources in an optimal way, while in the islanded mode, they additionally need to operate in grid-forming mode by providing frequency and voltage regulation, balancing services for resource adequacy, and all the other services like the operators of the larger power systems would need to do to ensure the safety of the energy supply (Parhizi et al., 2015).

However, in the grid-connected mode, multiple networked microgrids, with the excess power of their DERs and dispatchable loads, can offer considerable flexibility to DSOs to be used for their needs—for the benefits of the distribution grid as a whole (Alam et al., 2018; Li et al., 2017; Wang et al., 2014). These services, in these conditions, are the same as in the case of DER Aggregators. Through proper integration of a grid-aware Utility DERMS, and multiple Microgrid Controllers that are responsible for individual microgrids, DSOs may have enough flexibility to perform NWA for optimizing the grid, increase the reliability of the grid, as well as defer or even avoid costly and time-consuming network reinforcement. Testing the integration capabilities of Utility DERMS and Microgrid Controllers is well underway around the globe, and pilot projects have been performed that are showing promising results (Singh et al., 2020). Finally, even though Microgrid Controllers do manage DERs and dispatchable loads inside the microgrid, from the DSO's perspective, they are more flexibility providers than actual DER management solutions. Thus, they should not be called DERMS. Microgrid Controller is a much more appropriate term for these entities, and it prevents the confusion regarding the specific roles and responsibilities of distinct solutions.

Thus far, centralized and decentralized DER management solutions are discussed. In the next section, an integration of these two classes of DER management will be discussed, along with the benefits that this integration may provide to both DSOs and end-customers as a hybrid class of solution.

6 | HYBRID DER MANAGEMENT SOLUTION: INTEGRATION OF CENTALIZED AND DECENTRALIZED SOLUTIONS

Even though both centralized and decentralized DER management solutions may be deployed as independent solutions (decentralized not always though, as discussed in the previous section), their combination can provide additional benefits to stakeholders, as their technical values are enhanced when integrated and utilized together. When they are properly integrated, and set to work in coherence, they can cover a wider range of services that either class independently can, for an efficient management of an ever-increasing penetration of DERs, regardless of their type, rating, or location. In other words, integrated together, Utility DERMS, DER Aggregators (VPPs and DR providers included), Local Electricity Market Operators, and Microgrid Controllers would open a new world of possibilities for DSOs to utilize DERs as indispensable resources in performing a broad set of required operations and services, both grid-related as well as customer-related (Petrovic et al., 2019; Strezoski et al., 2022).

DER Aggregators and Microgrid Controllers could highly enhance DSO's awareness of behind-the-meter DERs and their impact on the grid conditions through communication with a Utility DERMS, and if the regulation allows, an ability to use their aggregated flexibility. Furthermore, once the regulation allows DERs to enter electricity markets, integration of a Utility DERMS with DER Aggregators and Local Electricity Market Operators will be of a high importance, as the schedules of DERs and DER Aggregators, aimed for market participation, would need to be checked and validated against technical grid constraints, which only a Utility DERMS would be able to do. It is important to note that regulations may vary at different parts of the world, and in some cases DSO would be able to reach behind-the-meter DERs (either directly or indirectly), whereas in other cases only private companies (DER Aggregators or flexibility providers) would be allowed to reach and use behind-the-meter DERs, but whichever case it is, planned operation of these resources would need to be validated against technical constraints, and a Utility DERMS is an essential piece in enabling efficient and violation-free management of high penetration of dispersed DERs.

Furthermore, if the local energy regulation allows, through its advanced applications for constraint management and grid optimization, and through integration with DER Aggregators, Microgrid Controllers and Local Electricity Market Operators, Utility DERMS would be able to offer DSOs ability to utilize the flexibility of all DERs, and to enable efficient and cost-efficient way of managing the grid in real-time. Otherwise, if the regulation does not allow DSOs to use behind-the-meter DERs and their flexibility, this integration will at least enable a Utility DERMS to gain additional insight into real-time and forecasted behavior of grid-edge, behind-the-meter assets and their impact on grid conditions, and in that way enable DSOs to better plan the integration of new DERs.

Another aspect is uncertain behavior of renewable DERs (especially solar and wind), that can cause issues to the distribution grid and its customers. It can be handled through Utility DERMS integrated with DER Aggregators. Namely, Variability of DER output, caused by their uncertain nature, is detected through measurements and weather forecast. Consequently, these results are detected in Utility DERMS through its integration with AMI and SCADA systems, as well as through integration with DER Aggregators, and are further used in State Estimation, Load and Generation Forecast, as well as in other advanced applications. For most critical cases of sudden and considerable variability, that has not been predicted by the Forecast engine, Utility DERMS can predefine interdependent behavior of its variable DERs and other flexible resources (energy storages, other DERs, DER Aggregators in the affected area, etc.), and set them to change their output and/or schedules on any variability above the threshold. For example, Utility DERMS can be set to dispatch a neighboring battery to start discharging with a preset amount, if the production of a solar PV goes beyond a specified threshold. Further on, based on State Estimation and Forecast results, advanced applications for real-time and LACM and grid optimization can detect the variability and automatically recalculate the new grid conditions, availability of flexible resources (both traditional and DERs), as well as technical constraints and potential violations. It will automatically re-dispatch all the resources on their disposal to return the grid in a violation-free and optimal state, or it will proactively change the schedules on DERs and/or Aggregators, to avoid predicted violations. Several examples of pilot projects in Australia where the integration between a Utility DERMS, DER Aggregators, Microgrid Controllers, and Local Electricity Market Operators has been tested can be found at (ARENA, 2020, 2021a, 2021b; Horizon Power, 2019; Singh et al., 2020). Results of these projects that are already available show benefits that DSOs and end-customers may achieve through the integration of centralized and decentralized DER management solutions, some of which are: increased observability, increased efficiency in scheduling DERs' operations, prevention of congestions and voltage problems, as well as economic optimization of DERs. Hence, this integration, if properly performed, ultimately leads to optimally and efficiently managed emerging distribution grids.

A high-level overview of such an integration is depicted in Figure 6 (the idea for this figure is borrowed from Schneider Electric, 2021, and the author has expanded it for this research). In Figure 6, regarding market operators, word "Local" is enclosed in parentheses because, as discussed in this and the previous section, regulations have still not been aligned around the issue of if the aggregated DER power should be offered on the local market, to Local Electricity Market Operators, or directly to the TSO on the wholesale market (Birk et al., 2017; Bjarghov et al., 2021; Gerard et al., 2016; Givisiez et al., 2020; Lund et al., 2019). However, as already discussed, in either case, a Utility DERMS would need to validate the schedules against the distribution grid level technical constraints.

7 | MOVING FORWARD TOWARD ACTIVE AND DYNAMICALLY CHANGING DISTRIBUTION GRIDS

In this section, this author's viewpoint pertaining the preconditions that should be accomplished to enable an efficient transition to active and dynamically changing electrical distribution grids is summarized.

7.1 | DERMS as an idea: all levels integrated in a single logical concept

To properly enter a new era of active and dynamically changing electrical distribution circuits, an intelligent and robust platform that would be able to integrate and communicate with all DERs, from behind-the-meter ones connected to the LV grid (individual EVs, rooftop PVs, household batteries, etc.), to large-scale DERs connected directly to the MV grid is inevitable. Further, such a platform would require a capability to provide awareness of the entire grid conditions in real-time, as well as ability for operators and grid engineers to analyze and control the influence that DERs impose on grid assets and to manage, protect, control, and economically optimize such complex systems with high amount of DERs, dispersed at all voltage levels. Finally, when regulations allow, it would need to enable an efficient market participation for DERs and aggregated DERs, toward achieving fair and profitable flexibility utilization. However, as discussed in previous sections, such a comprehensive platform does not exist and it would be very hard to come up with one, as there are several hierarchical levels of DER management solutions, each able to provide just a share of the required tools.

Thus, it is this author's belief that DERMS should be understood as a logical concept—a hybrid platform composed of all these solutions integrated together, that is, Utility DERMS, DER Aggregators, Microgrid Controllers, and Local Electricity Market Operators, and only if such an integration is correctly designed and developed, DSOs as well as end-customers will have an open door to proceed toward a new world of active and dynamically changing distribution grids,

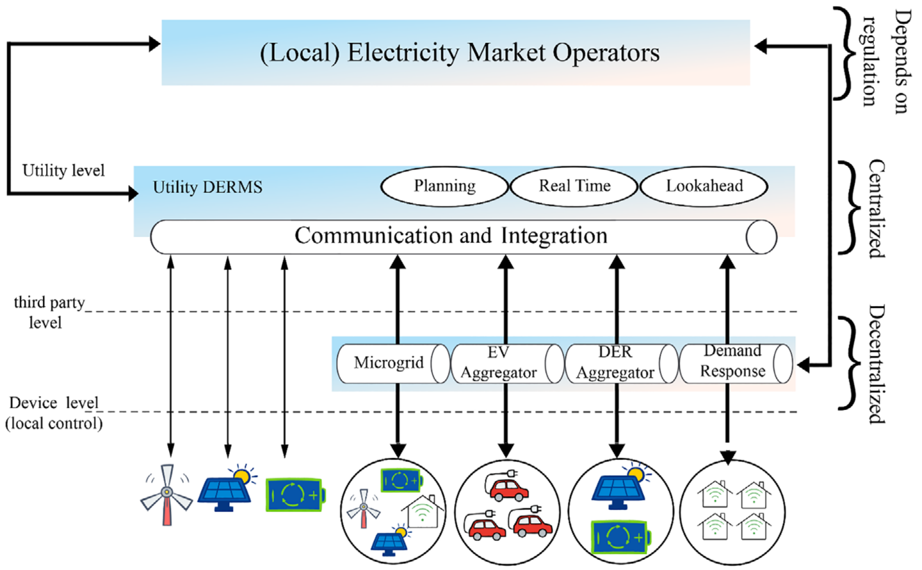

FIGURE 6 Integration of centralized and decentralized distributed energy resource (DER) management solutions

with high share of renewable DERs and electrified transportation. Therefore, a significant effort should be put in developing such an integration which would enable full spectrum of services required from DSOs in a new environment, and which would enable customers to utilize their full potential with their available flexibility and economically justify the significant rise of renewable DERs and EVs.

However, currently, the biggest obstacle for achieving this goal is the regulation framework that, even if exists, widely differs within different parts of the world. As already discussed in this article, as well as in multiple sources in literature (Birk et al., 2017; Bjarghov et al., 2021; Gerard et al., 2016; Givisiez et al., 2020; Lund et al., 2019), some important questions have still not be answered, such as: should DSOs have a responsibility and allowance to directly reach and use the flexibility providers, should the aggregators offer their service to a DSO, or directly to the TSO—this issue is additionally discussed in the next subsection, who is responsible for ensuring the reliability inside the distribution grid (considering market schedules and priorities), and so on. (Bjarghov et al., 2021). Thus, a regulatory reform that will clearly answer these and other important questions regarding DERs' roles and responsibilities, is a prerequisite for achieving the aforementioned goal of having a robust and intelligent hybrid DERMS platform that will enable efficient and optimal operation of emerging distribution circuits.

7.2 | Fully integrated TSOs and DSOs

As the proliferation of DERs increases and reaches levels that are considerable from all aspects, the role of DSOs is evolving and is expected to become much more important (ARENA, 2020, 2021a, 2021b; Birk et al., 2017; Bjarghov et al., 2021; Gerard et al., 2016; Givisiez et al., 2020; Lund et al., 2019). High levels of DERs are becoming considerable even from the TSO's stance, and much tighter TSO-DSO coordination is required. TSOs are becoming interested in using aggregated DERs for their needs, such as balancing supply and demand, frequency regulation, ancillary services, and even energy trading, which can be provided only if a tight TSO-DSO coordination is properly achieved.

A significant large body of literature, all cited here, agree that decoupled TSO and DSO model is not sustainable anymore, and with the increase of DERs, new coordinated models must emerge (ARENA, 2020, 2021a, 2021b; Birk et al., 2017; Bjarghov et al., 2021; Gerard et al., 2016; Givisiez et al., 2020; Lund et al., 2019). There are various TSO-DSO models proposed in the literature, and the most promising will be summarized as follows.

In Gerard et al. (2016), five different models for TSO-DSO coordination for electricity market purposes and DER control have been proposed. First, a Centralized ancillary service market model is proposed, where a TSO has a full control of the entire market and resources on both transmission and distribution level, and a DSO is only concerned with keeping distribution grid in a violation-free operating conditions—which is very hard to be provided in such a model. Second proposed model is a Local ancillary service market model, where the DSO organizes a local market for resources connected at the distribution grid and, after solving local grid constraints, aggregates and offers the remaining bids to the TSO. These two models were also presented in (Birk et al., 2017) as "Initial" and "Subsequent" phase of DER market deployment. Third model in Gerard et al. (2016) is a Shared balancing responsibilities model, where balancing responsibilities are divided between TSO and DSO according to a predefined schedule. Fourth and fifth models are Common TSO-DSO ancillary service market model and integrated flexibility market model. In these models, the TSO and the DSO have a common objective to decrease costs to satisfy both the need for resources by the TSO and the DSO, where in the fifth model nonregulated market parties are additionally enabled to participate in the market.

In Givisiez et al. (2020), three models for TSO-DSO coordination are discussed, along with their advantages and disadvantages. The models are: (1) TSO managed model, (2) TSO-DSO hybrid managed model, and (3) DSO managed model. In a first model, the main advantage is a clear line of command, that comes from the TSO for all resources (including DERs), but the main disadvantage is that in this case DERs can be extensively pushed to their limits and if there is no a DER management tool, their schedules would likely cause violations in the distribution grid. In a Hybrid managed model, DSO keeps the control of DERs, which would likely lead to the more efficient use of DERs (of course, only with a proper DER management tool is available), and DSO validates the schedules received from TSO, against the technical constraint validations. Finally, in a DSO managed model, DSO is responsible for the entire communication, coordination, and scheduling of DERs, where the TSO issues only aggregated bids, for the entire DSO-controlled area.

It is difficult to assume any of these models could work properly and in a sustainable way without causing violations in the power system, if a proper DER management tool does not exist. Thus, it is this author's belief that DERMS can contribute the most to implement any of these models in practice. Through the integrated DERMS solution, DSOs would be aware of the real-time, as well as predicted flexibility of the aggregated DERs from all voltage levels, that could consequently be offered to TSOs to be used for their needs. Such flexibility is a considerable asset for TSOs and could eventually replace usage of expensive, often polluting, and inflexible traditional power plants. Moreover, improved coordination between TSOs and DSOs, and awareness and ability to use the aggregated flexibility of DERs through integrated DERMS, may lead to a much better optimization of investments in network enhancements (at both transmission and distribution levels), as it would offer NWA ways for solving congestions and other technical violations.

Overall, development of this coordination will certainly be accelerated and improved by increased participation of DERs (mostly through their aggregation) in power and energy markets, by adopting an appropriate model for TSO-DSO coordination, and by utilizing practice through an integrated DERMS solution.

7.3 | Standardization and unification of communication protocols

A significant obstacle toward the integration of centralized and decentralized technologies, including the integration of various DER management platforms, individual (large-scale and small-scale) DERs, as well as TSO-DSO integration, is there is no globally accepted communication protocol yet, nor an established interoperability standard adopted by all interested parties. There are various protocols used for different purposes, and even for the same purpose but supported by different vendors and DER developers, that leads to difficulties in implementing the appropriate and robust integration. Utility DERMS solutions, developed by different vendors, often use different protocols to communicate with DERs and DER Aggregators, further DER Aggregator solutions by different vendors utilize different protocols to reach individual DERs, and finally, various DERs may support distinct protocols for two-way communication with control centers and aggregators.

The most promising protocol to this author, which seems to be able to cover most if not all the required tasks, is the IEEE 2030.5, as it is able to be used by Utility DERMS, DER Aggregators, and individual DERs, for an essential two-way communication and data transfer (IEEE, 2018). IEEE 2030.5 protocol enables communication between Utility DERMS and DER Aggregators, as well as between either Utility DERMS or a DER Aggregator, with DERs (regardless of their size and the PCC location), and thus seems to enable a fully integrated DERMS solution, as envisioned in this article. Further, this protocol enables exchanging planned schedules of DERs and Aggregators with a Utility DERMS, modifying the schedules in real-time, sending individual or group commands to inverters (volt-var, volt-watt, frequency-watt curves, etc.) through DER management tools, and in that way it seems to provide the essential infrastructure for implementing a comprehensive DERMS solution, that would be able to communicate with all DERs, and when the regulation allows, control, and optimize their behavior.

To overcome this significant challenge, it is this author's belief that working groups consisted of representatives from academia, utilities, DER developers, and DER management vendors, should be formed to agree upon the optimal communication protocol(s) for DERMS, and consequently stick to the agreed protocols to enable efficient and robust integrated DERMS platform and a proper TSO-DSO coordination.

Nevertheless, it should be clear that the willingness of DERMS adoption worldwide is rapidly rising—as per the report issued by Navigant, titled “VPPs and DERMSs: Different Sides to the Same Coin” (Navigant, 2019), the annual spending by utilities and DSOs on implementing DERMS and VPPs (centralized and decentralized DER Management solutions in this article, respectively) is significantly rising in the last several years, and it is expected to rise even more. Namely, per this report, from around 750 million US dollars in 2018, the spending on VPPs and DERMS is expected to reach almost 4 billion US dollars in 2027. Note that this is marked as an optimistic scenario in the report. On the other hand, as per the report published by the consulting firm Market and Market (Market and Market, 2021), DERMS market alone (“Utility DERMS” in this article) is expected to rise from 286 million US dollars in 2021 to 750 million US dollars in 2026., at a CAGR of 21.2%.

However, to perform a DERMS implementation properly and efficiently, especially in the emerging conditions with a rapid increase in DER penetration worldwide, the challenges discussed in this section need to be properly solved.

8 | CONCLUSIONS

Due to the monotonically increasing trend in penetration of DERs, encouraged by renewable energy targets and initiatives for electrification of transport around the globe, distribution circuits are becoming active and dynamically changing systems. In this new environment, operators and grid engineers are struggling to cope with novel challenges by using legacy tools and procedures, and it is evident that these are not sustainable anymore. To enable proper tools to cope with new challenges, novel software solutions for DER management are emerging. This article provided a comprehensive state-of-the-art review of different DER management solutions, currently available.

On one hand, centralized and grid-aware enterprise solutions aimed to enable monitoring, control, and protection of the entire grid with high penetration of DERs evolved as a response to inability of legacy control centers to respond to new challenges. These enterprise solutions are termed Utility DERMS in this article. On the other hand, decentralized DER management solutions, aimed for aggregation, market participation, demand response, and other customer-related services, evolved as a response to challenges that high amount of dispersed DERs introduce at the customer level. These solutions are divided into DER Aggregators, Microgrid Controllers, and Local Electricity Market Operators in this article. Decentralized DER management solutions should be understood as a one level below Utility DERMS, in a hierarchical structure of DER management solutions, as Utility DERMS uses them as its resources for constraint management, grid optimization, and DER market participation.

The analysis provided in this article determines a more efficient DERMS could be achieved via proper and robust integration of centralized and decentralized DER management solutions. This approach is envisioned as an enabler of an efficient shift toward active and dynamic electrical distribution grids. Such integration could lead to overcoming the challenges that DERs impose, and it would benefit all the power system participants, including TSOs, DSOs, as well as end-customers.

This article concludes that the main obstacles currently standing on the way of achieving this transformation are: (1) Unclear regulatory framework regarding roles and responsibilities of DERs and DER management solutions, as well as electricity markets that are still in their infancy stages; (2) Weak TSO-DSO integration; and (3) Ununified communication protocols, with different communication and integration logic implemented by different vendors. This sets the basis for future research in this direction and further development of DERMS.

AUTHOR CONTRIBUTIONS

Luka Strezoski: Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); software (equal); supervision (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST

The author has declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Luka Strezoski https://orcid.org/0000-0003-0109-4320

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AUTHOR BIOGRAPHY

Luka V. Strezoski is an Assistant Professor, Head of the Power Engineering and Applied Software Department, and Director of the Smart Grid Laboratory with the Faculty of Technical Sciences, University of Novi Sad. He holds a secondary appointment as a Principal Consultant and Member of the Technology Board with Schneider Electric. Dr. Strezoski received the BS, MSc, and PhD degrees (with honors) in Power Engineering from the University of Novi Sad, Serbia, in 2013, 2014, and 2017, respectively. His PhD research was conducted in a joint research between University of Novi Sad, Serbia and Case Western Reserve University, Cleveland, Ohio, USA. His interest is in distribution system modeling and protection; renewable generation modeling; integration and active management of high penetration of renewable DERs; DMS and DERMS power applications, as well as microgrid modeling and protection. Dr. Strezoski serves as an editor in several international journals, including Guest Editorial positions for IEEE Systems Journal and Elsevier's International Journal of Electrical Power and Energy Systems, as well as Topic Editor for MDPI's Electronics journal. Dr. Strezoski is a Member of IEEE and PES, as well as a Member of the Assembly of the Serbian CIRED section.

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