Distributed Energy Resources: Operational Benefits

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1. Introduction

In the current context of energy transition, the first step to ensuring the cost-effectiveness and reliable operation of a network is the use of appropriate planning tools. These tools must assess the real need for strengthening, replacing, and integrating new grid resources, taking into account not only technical and regulatory issues, but also the operational benefits of distributed energy resources (DER), including renewable energy sources (RES), electricity storage (ESS) and electric vehicles (EVs). All this makes for a promising research challenge. As a result, several key ideas and messages related to the optimal integration of distributed energy resources (DER) into energy distribution networks were recently published in scientific journals related to energy issues. Some of the articles and their contributions are presented below.

From a more theoretical viewpoint, in Rebollal et al. [1], the authors analyze the state of 23 distributed-generation and microgrid standards. Among them, 18 correspond mainly to distributed generation, and five introduce the concept of microgrids. The analysis and comparison focus on several topics, namely connection criteria, operating conditions, control capabilities, power quality, protection functions, and reference variables. As a result, IEEE 1547 is identified as the most complete standard. Another purpose of the article is to analyze and compare the diversity of standards. Older standards were developed on the assumption that the percentage age of DER in the network was relatively low. Nevertheless, in order to improve stability as the number of DER facilities increases, new standards are being developed, including advanced requirements for interconnection and DER operation. The conclusions note significant differences between the standards, as exemplified in the operating conditions section, of up to 40% in equivalent threshold settings for too-low voltage and 2.8 Hz for too-low frequency. Therefore, there seems to be a clear need to define a common framework for DER standards and microgrids in the future, where themes, terminology, and values are expressed to broadly encompass all diversity in a way similar to that of the network transport level in ENTSO-E codes or the proposed uniform structure. The article is a very good analysis of distributed energy resources (DER) and wetlands.

Wang et al. [2] discuss the issue of a multi-criteria assessment of a distributed energy system based on the relational-anti-entropy ratio method. Today, a distributed energy system can be a clean and low-carbon way of using energy that can realize nearby renewable energy consumption, guarantee energy supply and improve the urban living environment. Thus, the assessment of the distributed energy system should be comprehensively linked in terms of social, technological, economic, and environmental benefits. The authors propose a solution: a model for assessing a distributed energy system. The model of a total of 23 indicators is constructed based on four criteria of technology, economy, environmental protection, and society. The energy system is evaluated by combining the method of the sequential analysis, used to determine the meaning of each criterion through expert stratification to obtain a subjective weight, and the method of weighing. The tests provide evidence in favor of this approach, both in terms of performance and model precision.
Kolcun et al. determined the efficiency and appropriateness of the energy systems in Poland and Slovakia. They focused on the suitability of using a particular instrument depending on the conditions in the country especially energy consumer taxation, the level of tariffs, and tradeable certificates. The results showed that the changes in primary energy consumption had a significant inversely proportional impact on the proportion of renewables within Poland. Slovakia has also confirmed the presence of a significant negative impact of primary energy consumption on the percentage of renewable energy sources usage [3]. However, there is less difference between the two compared countries.

Nycz-Wróbel [4] researched Polish enterprises are most often carry out activities related to the use or improvement of technologies and the implementation of emission monitoring and measurement systems. This indicates a gradual transition to the use of renewable energy.

Rus et al. [5] performed an depth-analysis and forecast of renewable energy generation and consumption across 2030 in the EU and showed a fast increase in renewable energy capacities and distributed generation. In addition, fast penetration of renewable energy sources and distributed generation has an impact on the development of EU trade in energy [6]. As well, one of the tools for influencing the transition to renewable energy is the implementation of green bonds and green projects by the World Bank and the European Bank for Reconstruction and Development [7].

The authors Bodjongo et al. [8] studied the availability of renewable energy for rural and urban enterprises. The results showed the presence of discrimination based on location, gender of managers, type of activity, business environment, and professional experience.

Meanwhile, Fichera et al. [9] demonstrate the performance of a local hybrid distributed energy system serving urban communities. In this regard, the local microgrid is compared with the traditional centralized configuration, in which the demand for electricity is completely met by the main grid. The comparison is based on energy, environmental and economic issues assessed taking into account primary energy savings, carbon avoidance, and simple payback period indicators. The proposed system was previously simulated using an agent model implemented in the NetLogo software using as input data on the spatial position of the building and electrical load, structural dimensions, and roof characteristics for the photovoltaic installation (exposure, shading, orientation, and typology of the roof). The authors of the study consider the system based on photovoltaic installations installed on the roofs of about 370 buildings (located in the south of Italy) connected by a local electrical microgrid. The results show that the results of the environmental analysis are consistent with the results of the energy analysis, emphasizing that avoided carbon dioxide emissions increase with the installed photovoltaic energy and the permitted spatial reciprocal distance of electricity exchange between local microgrid agents.

Chwieduk et al. [10] discuss the possibilities of moving from centralized energy systems to distributed energy sources in large Polish cities. The general problem concerns the possible transition from existing centralized energy systems in Polish cities to modern low-carbon distributed energy systems based on locally available energy sources, mainly solar energy. In the article, the authors present a solution that seems to be technically simple, as well as energy-efficient, producing a significant reduction in primary energy consumption, which is also in line with the latest trends in achieving self-sufficient energy in new housing estates and sustainable development in energy systems. The results of the authors’ research show that the use of micro-scale photovoltaic systems would help residential buildings obtain more energy, significantly reduce energy consumption based on fossil fuels, and even if the grid cannot be used as virtual storage of electricity, direct self-consumption can reduce energy consumption by an average of 30%. Therefore, it seems that this approach can be used as an opportunity to move from centralized energy systems to distributed energy sources.

Another paper explores the application of energy management strategies to overcome the challenges of integrating distributed energy resources into microgrids. In Rezaeimozafar et al. [11], the idea is to eliminate the multi-objective problem of optimiza-
tion by minimizing total power costs, power losses, and voltage deviations. To this end, the authors use an innovative model to minimize this problem consisting of three technical and economic parts: power losses, voltage fluctuations, and demand-supply costs. The optimal capacity and positions of DERs based on probabilistic models are defined as the outer layer. The inner layer corresponds to the charging and discharging schedule of electric vehicles and ESS using a fuzzy logic-based ICM. The formulated goal function is solved using the GA-PSO algorithm, and the Fuzzy membership-based approach is used to obtain an optimal solution from the Pareto boundary. The results indicate that optimized DER penetration into the distribution network improves system performance indicators (e.g., voltage deviation in sensitive buses). The use of ICM for electric vehicle charging planning and ESS has significantly reduced voltage fluctuations and power losses. The proposed method has also enabled new functionalities for RES, e.g., they can act as distributed generators. The results are presented in eight different scenarios, proving the validity of this approach.

Optimization of distribution energy systems and DER is another topic that numerous papers focus on these days. Darbali-Zamora et al. [12] state that real-time state estimation using a digital twin can overcome the lack of field measurements inside the power line to optimize the network services provided by distributed power sources (DER). The authors use a technology called Programmable Open Management Distribution Resource Optimization System (ProDROMOS) in a simulated RT environment as well as a hardware-in-the-loop photovoltaic inverter and a field demonstration with a 678 kW photovoltaic system in Grafton (MA, USA). Key results indicate that the PSO OPF method had difficulty improving supply voltages because the feeder was unbalanced, but the phase mean was close to nominal. As a result, it was difficult to improve the live system, and the PSO OPF solution was a PF setting close to unity. However, the PSO OPF solution was able to determine the optimal PF in RT using a digital twin with minimal field telemetry, which showed that the digital twins of the feeders could overcome the limitations of field measurement to generate condition estimates and generate centrally optimized DER setpoints. The results also show that the use of PHIL can help with identification. The main contribution of the authors is the effective demonstration of how the digital twin RT provides pseudo-measurements of state estimation that can be used to optimize DER operations for regulating the distribution voltage.

Bintoudi et al. [13] demonstrate optimal framework planning for both next-day and real-time microgrids. This framework evaluates the operation in real-time and, based on deviations, dynamically optimizes the schedule to continuously deliver the best solutions in terms of economic benefits and energy management. The authors present the design and application of an optimal scheduling scheme, adapted to those connected to the grid, fully based on MG RES, with DER coupled with alternating current. The authors implemented the designed framework in a real microgrid plant consisting of: residential loads, a photovoltaic board, and a storage unit. Research shows not only the benefits of optimal daily advance planning, but also the importance of dynamic re-optimization in case deviations occur between forecasted values and real-time values given the irregularity of photovoltaic power generation, as well as the stochastic nature of consumption.

Dzikowski [14] discusses the issues of coordinating the planning of day-ahead operations using distributed energy resources. The overall problem is as follows: the lack of a comprehensive method to ensure coordinated OSD-TSO operational planning of the different resources available in different transmission and distribution systems in order to efficiently account for residual load costs and variability. The author undertakes a very difficult task—to show the concepts of radial distribution systems that are directly connected to the transmission system via single T-D interfaces (e.g., transformer and DC link) and a transmission system that is managed according to the model of a central control room. RRs considered by the author include photovoltaics, wind turbines, biofuel-fired electricity sources, energy storage systems, and active electricity consumers with the possibility of temporarily reducing their load. For this purpose, analysis is conducted for an
optimization model that generates a 24-h power profile on the T-D interface, which is much more attractive than an unmodified profile resulting from the self-shipping of local DER. Simulations carried out by the author on the transmission system model indicate that fewer conventional power plants have to operate during the day if the distribution systems have modified profiles on T-D interfaces. Importantly, there are also much fewer start-ups and shutdowns of power plants, and their output capacities are less variable compared to the scenario in which there is no DER coordination and only an independent control room. The results show the superiority of the proposed model over other models.

The issue of planning an electricity distribution system taking into account distributed energy resources is examined by Picard et al. [15]. In the current context of the energy transition, the first step to ensuring the cost-effectiveness and reliable operation of the grid is the use of appropriate planning tools. The actual aim of the article is to show that thanks to the large-scale implementation of smart grids with the accompanying advanced control and measurement infrastructure, it is possible to improve the classic methodologies of distribution network planning using available information and data. The authors prove that the proposed methodology streamlines the classic distribution network planning process by applying DER integration from a network perspective, using the information available through the implementation of smart grids. In addition, the proposed methodology has been successfully tested in a real network distribution with 450,000 delivery points over a geographical area of 5000 km².

The issue of planning and decision-making related to distributed energy is explored by Schmeling et al. [16]. The study presents a tool based on the oemof.solph simulation environment, which creates an optimal delivery concept through optimal sizes and Monte Carlo-based risk assessment. The case study of this study is a district that is to be built on the site of the former Oldenburg air base in northwestern Germany. The district was designed as a living laboratory to test Smart City innovations. Unlike other studies, the authors present an interdisciplinary, application-oriented, and holistic approach, which applies to all phases of planning and operation of supply infrastructure, combining energy technology with energy industry issues.

The strengthened coordination strategy for a distributed energy aggregator participating in the day-ahead reserves market is also addressed by Guzman et al. [17]. They point out that the integration of distributed energy resources (DER), e.g., electric vehicles (EVs) and renewable distributed generation (DG), in the electricity distribution system (EDS) benefits society but also introduces technical challenges (e.g., congestion and voltage issues). This study proposes a linear programming model for an aggregator’s coordination strategy to maximize its profit by managing DER and its share of the day-ahead reserves market. The model uses electric vehicle charging control to provide an up/down reserve and reduces costs by using dg. The proposed mathematical model represents a daily EDS operation (hourly resolution) to enforce limits on voltage and current size. The case study shows that tests carried out in a 34-bus distribution system make it possible to determine the strategy for an aggregator that simultaneously increases profits, contributes to guaranteeing the operation of the electricity distribution system, and meets the requirements for charging electric vehicle traffic.

Meanwhile, Trinh and Chung [18] explore a strategy for controlling DER in low-voltage DC microgrids to minimize operating costs and keep the distribution voltage within the normal range on the basis of intelligent planning for charging and discharging EV vehicles and the use of renewables such as photovoltaic (PV) installations. In the study, the authors use electric vehicles available in the DC distribution system to optimize the total operating cost and control the regulation of voltage. The proposed optimal control strategy is formulated using MILP at a 24-h level with 1-h sliding stages. The conclusion is that, in normal operation, the proposed method encouraged the charging of electric vehicles at a low electricity price and discharge at a high electricity price in order to minimize the total operating cost. On the other hand, when there was a problem with the undervoltages, electric vehicles were forbidden to charge and encouraged to discharge.
in order to compensate for the voltage problem. In addition, the limitations of connected electric vehicles were found to meet the SoC level requirements required by the electric vehicle owner.

The real impact of cost and greenhouse gas optimization and minimal charging of electric vehicles in distributed energy systems is investigated by Schulz and Hufendiek [19]. To this end, the authors focus on the end user of charging an electric vehicle, having different goals: minimizing the cost of purchasing household energy and minimizing greenhouse gas emissions. These goals are sometimes competitive and generally cannot be achieved at the same time, as the authors’ results show. The authors assume a detailed travel profile of a household equipped with a local generation and storage system at the same time, and use different strategies to compare the impact on annual greenhouse gas emissions and the annual costs of energy purchase by a household. The results indicate that there is almost no real impact on actual greenhouse gas emissions in the overall system. Therefore, the inclusion of this greenhouse gas emission target in the objective function increases costs.

Another paper presents a project for distributed energy storage in an electric vehicle for smarter mobile applications. In their research, Raman et al. [20] present HESS supercapacitor-battery analyses, including a simple model of a lithium-ion battery, a supercapacitor, and a bidirectional interleaved converter (BIC). The authors use three performance indicators: hybrid power ratio (HER) $\kappa_e$, hybrid peak power ratio (HPPR) $\kappa_{pp}$, and hybrid average power ratio (HAPR) $\kappa_{ap}$. The research conducted on the performance of the developed converter and the car was presented with the mileage captured while driving the car on the dynamometer. As a result, the authors note that the construction of the vehicle system is well thought out, while the features and functions of BSMS, VCU, HESS, DC-DC converter, and inverter are clearly explained. The proposed system is stable and can be controlled with a simple energy management technique to share the power required by the inverter. Finally, the PI control can be used to implement an energy management strategy with reference parameters set by the user.

In addition, Mominul Hasan [21] explores electric rickshaw charging stations as distributed energy storage for the integration of intermittent renewable energy sources in Bangladesh. Renewable energy, whether based on wind or solar power generation, requires one key element: batteries to store the energy produced. Therefore, the author shows the electric rickshaw as an option for energy storage using modern technologies. The article details a case study of the innovative control procedure of the proposed CBESS. This method helps in battery management and extends battery life. The author’s simulation of the microgrid shows the potential of RE integration in a small community. The result of the simulation indicates that the integration of RES not only reduces energy costs, but also helps to generate income through energy exports. The results show the perspective for further research not only in e-rickshaws, but also in other societal possibilities of energy storage in developing countries.

The issue of optimal planning of electricity storage systems in microgrids in order to minimize costs is explored by Mottola et al. [22]. In the study, the authors propose a strategy for minimum ESS planning costs in $\mu$G that avoids costs by taking into account voltage drop compensation. The proposed method is based on a multi-step planning tool that allows the user to identify the optimal location and size of storage systems. The results of numerical simulations carried out by the authors clearly show that compensation for the voltage drop made for significant economic benefits. Of course, these benefits strictly depend on the cost assumed for voltage drop events, which can only be determined by end users with comprehensive knowledge of the issue. The article is a very convincing illustration of the optimal planning of electricity storage systems in microgrids.

Jin et al. [23] discuss the issue of optimizing the location and capacity of peak-Shaving’s distributed energy storage system. The general problem is this: Distributed Energy Storage System (DESS) technology does a very good job of the challenge. However, the number of devices for DESS is much larger than the central energy storage system (CESS), which brings
with it challenges for solving the problem of location selection and capacity allocation on a large scale. A simulation based on a greedy algorithm with Monte Carlo simulation was used to find the optimal location to install DESS and the optimal power allocation scheme. A case study conducted by the authors confirms the superiority of this method. The results of the study indicate that DESS is difficult to launch without sufficient subsidies within the current costs. In addition, the load distribution determines the location and capacity allocation scheme, attracting more capacity in high-load nodes to improve power flow.

Location is also the focus of Lin et al., who write about the faults based on data in distribution systems with distributed energy resources [24]. In their deliberations, the authors propose a novel data-driven fault localization strategy based on quantitative error confidence levels in DER distribution system subregions. This strategy relies on a tree segmentation criterion to divide the entire system under study into several subregions, and then combines Support Vector Data Description (SVDD) and Kernel Density Estimation (KDE) to find the confidence level of error detection in each subregion in terms of the corresponding \( p \)-value. By comparing the \( p \)-values, you can accurately locate the errors. In the study, the authors prove that compared to the traditional relay-based approach, the proposed data-driven fault location is able to accurately locate the fault even with systems integrated with DERs. The results of the experiment show that the proposed fault location strategy can narrow the scope of suspected faults and ultimately successfully locate the fault on the specification line.

Finally, Xinming et al. [25] propose a local soft open point (SOP) control strategy to suppress voltage fluctuations when adding a renewable energy source to the system. This research focuses on taking into account both active and reactive SOP power to regulate the voltage of the supply nodes based on line impedance, which can take full advantage of the apparent SOP power. The mathematical model used for the network connected to the SOP is determined based on the characteristics of the low-voltage distribution network. Compared to the existing single reactive power compensation strategy based on a photovoltaic converter, the study results show that SOP-based mixed compensation works better at voltage attenuation and consumes less visible power in a distributed low-voltage network. In addition, the local control strategy proposed by the authors can react quickly to address uncertainties about DG performance compared to the traditional strategy. Overall, SOP intervention provides more outlet space for renewable energy generation, which increases its adoption.

2. Conclusions
In this review, we discussed articles related to various aspects of distributed energy, ranging from a review of standards and guidelines for microgrids and distributed energy resources, novel methods, and approaches, to local strategies to control the suppression of distributed energy fluctuations based on a soft open point. New models and approaches combined with fresh ideas based on the latest challenges are pushing economic science forward. Besides, energy consumption challenges and linked environmental issues belong to essential constituents of quality of life perception [25] developing the background for scientific discussion and investigation on environmental taxation [26], measures to support renewables due to the positive externalities of their use [27] and other regulatory policy tools in the energy management area.

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