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On Integrating and Operating Distributed Energy Resources in Distribution Networks: A Review of Current Solution Methods, Challenges, and Opportunities

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ABSTRACT The growing demand for electric power and the need for an energy transition that contributes to the reduction of global greenhouse gas emissions have driven the development of various energy generation, storage, and offset technologies. These technologies are known as *distributed energy resources*. Their integration into distribution power systems not only contributes to improving operating aspects, but also allows supplying electricity to areas that do not have access to large-scale power systems. Therefore, the integration and management of these resources has become a topic of interest, and several studies seek to optimize their impact on technical, economic, and environmental aspects. However, this optimization poses specific challenges related to the type and number of variables related to the operation of a distribution power system. This review article aims to describe the main challenges posed by three-phase AC three-phase distribution power systems under scenarios involving the integration of distributed energy resources. In addition, it presents some approaches proposed by different authors to improve the technical, economic, and environmental aspects of power grids. It can be stated that the strategies presented in the literature fail to consider scenarios that simultaneously integrate different types of technologies and optimize them while following a multi-objective approach and considering three-phase systems in a context of variable generation and demand. Therefore, future work in this field should address these aspects in a holistic manner, taking into account the computation efforts and processing times required by intelligent algorithms.

INDEX TERMS Electrical mathematical model, DERs, DG, Energy costs, CO_2 emissions, Energy losses, BESS.

I. INTRODUCTION

In recent years, the accelerated growth of the world's population has posed several challenges associated with the developments needed to ensure the worldwide supply of electrical energy [1]. Electric power systems (EPS) have enabled the generation, transmission, distribution, and control of this type of energy on a large scale. However, they face challenges of their own, which are related to the need for changes that allow meeting the growing energy demand. One of the most significant corresponds to the integration of renewable energy sources into the energy matrix. [2] [3].

The distribution stage is where the greatest challenges arise, as it is there that direct interaction with end users takes place [4]. These users have different characteristics, which make the system operation model complex and force network operators to adopt strategies aimed at analyzing technical, economic, and environmental aspects. These strategies must ensure the correct supply of electric power to all users, for which aspects such as power quality, voltage profiles, and line capacity are of vital importance [5].

Most electrical distribution systems (EDS) worldwide are built with a radial topology, as this implies low investment costs and constitutes the typical distribution of loads. However, this topology considerably increases energy losses and has impacts on the operating aspects of the system [6]. In a radial distribution system, current must flow through a single path to the loads, which, depending on the distance, can cause voltage drops in the nodes. Additionally, lines closer to the generation node experience high current flows, leading to increased energy losses due to the Joule effect [7].

Electrical energy is transported through three-phase connections with the objective of increasing power capacity and reducing losses. An ideal three-phase system assumes a power balance in each of its phases. However, each user connected to the grid requires a different type of connection (single-phase, two-phase, or three-phase) according to their consumption requirements (residential, commercial, or industrial) [8]. In this context, the power levels of each phase vary according to the type of connection and the users' consumption requirements. This variability contributes to voltage and current imbalances in the system. Unbalanced operation in an EDS system triggers a series of negative effects, such as increased energy losses, increased current flows (which affects the continuity of the service), and variations in voltage profiles. All of the above affects the reliability of the system and has a transversal impact on the technical, economic, and environmental aspects of the network [9].

Another significant challenge in the operation of EDS lies in their integration with large EPS. It is important to consider the topographical, social, economic, demographic, political, and cultural aspects of the territories within the influence areas of the EPS, as they determine whether an interconnection between EDS and large EPS is feasible. The geographic location and the relief of a region, as well as population density and growth projection, infrastructure cost, regulatory aspects, and cultural considerations are essential factors to evaluate the technical, social, and economic viability of interconnecting EDS with large EPS. If this interconnection is not possible, the EDS should operate independently in what is known as an *isolated area* [10].

Isolated areas are highly dependent on fossil fuels for electricity generation, leading to negative environmental impacts due to high pollutant gas emissions from these energy sources [11]. In addition, energy distribution is carried out using systems that, as in interconnected areas, have a radial topology, which represents both an operating problem due to the losses associated with the transport of energy and increased costs related to generation and distribution [6].

In light of the above, it can be concluded that both connected and isolated areas require strategies to meet their energy needs. However, in isolated areas, service continuity must also be guaranteed, which adds an additional complication in comparison with grid-connected networks. It is important to note that a system's technical, economic, and environmental aspects determine the efficiency of such strategies and their potential to impact social and economic development, as well as the end users' quality of life. Therefore, this topic is of great interest and has been the subject of various research projects that seek to improve these aspects.

In recent years, distribution grid operators have implemented strategies to improve the operating aspects of electrical systems. To this effect, they use energy generation devices based on renewable sources, energy storage devices, and reactive power compensation systems, which together are known as *distributed energy resources* (DERs) and allow for an adequate management of the energy needs of the grid [12]. DERs contribute to improving voltage profiles and reducing energy losses as well as the percent load on distribution system lines.

The impact of DERs depends on their proper integration and operation. Aspects such as the technology used, size, and energy injection and storage are of vital importance if the potential of these systems is to be fully exploited [13].

From a mathematical point of view, the DER integration problem is difficult to solve due to its nonlinear and nonconvex nature. Its mathematical formulation involves binary and continuous variables, which may belong to the real or complex domain [14]. In addition, each scenario involving the integration of generation, storage, and compensation devices must be validated via power flows that allow determining the state of the EDS variables, such as voltage levels and current flows. This validation must be carried out through methodologies that allow evaluating a large number of flows in acceptable processing times.

Some strategies focus on improving technical aspects, with notable topics including the reduction of energy losses [7], [15], [16], the improvement of voltage profiles [17]–[19], and the reduction of line load percentages [4], [20]. Additionally, economic aspects such as investment and operating costs [21]–[23] are addressed, alongside environmental considerations [24], [25], such as the reduction of greenhouse gas emissions. Optimization algorithms are used in these strategies to determine the most appropriate technologies, nominal sizes, injection levels, and energy storage solutions for each device [26].

A. CONTRIBUTIONS AND SCOPE

This article presents a review regarding the main challenges associated with the operation of three-phase AC EDS, as well as the strategies employed by grid operators to guarantee the supply of electric power. In addition, it provides a critical analysis of several strategies based on intelligent algorithms which contribute to improving the impact of DER installation on EDS. The limitations of each study are highlighted, as well as the need to simultaneously address them in future work.

B. ARTICLE STRUCTURE

The remainder of this article is structured as follows. In Section II, the operation of EPS is detailed, with a particular focus on the challenges that arise during the distribution stage. In addition, this section discusses strategies commonly employed by grid operators to improve system operation and ensure reliable power supply in both connected and isolated areas, and it summarizes the main advances and approaches presented by the specialized literature to address and implement the proposed strategies. Section III addresses the problem of DER integration in EDS through a critical analysis of several research works. Finally, Section IV presents the conclusions of our work, highlighting its main contributions, providing some recommendations, and outlining future lines of work.

II. ELECTRIC POWER SYSTEMS

EPS consist of multiple stages that allow effectively meeting energy demands. Figure 1 shows their three primary stages.

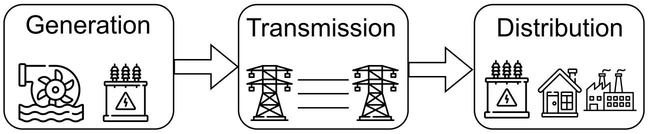

FIGURE 1: Stages of an electric power system

Each of these stages plays a crucial role within the system and has distinctive characteristics that define its operating model [2]. The first stage, and perhaps one of the most important, is the *generation stage*. In this stage, the conversion of energy from different sources takes place. Its main feature lies in the ability to obtain electrical energy through different processes (combustion, mechanical power, nuclear power, and the exploitation of the various forms of energy present in nature). In addition, at this stage, it is necessary to ensure that the amount of energy generated is sufficient to meet the demand while maintaining acceptable frequency and voltage levels in the system [27].

In large-scale EPS, electric power is generated far from the final consumption points, so it must be conditioned for transport over long distances. Once conditioned, this electrical energy is sent to the next stage, which is known as the *transmission stage*. The objective here is to ensure the efficient transport of energy over long distances. To this effect, transmission lines operate at high voltages, which reduces energy losses. In addition, by controlling electrical variables such as frequency and voltage, as well as through real-time monitoring of the system's operating conditions, it must be ensured that the transported power is stable and of high quality [27].

Once transported, the electrical energy reaches large consumption centers and must be conditioned again to move on to the *distribution stage*, where the energy generated is distributed and marketed. It is at this stage that the greatest challenges arise, given the direct interaction of the system with the end users [27].

A. CHALLENGES ASSOCIATED WITH EDS

The main objective of EDS is to distribute the energy coming from the generation and transmission stages among the end users. To this effect, proper energy management must be ensured. This has implications for aspects such as efficiency, reliability, quality, and energy demand, where the characteristics of EDS have a direct impact [28]. Figure 2 shows the main characteristics of EDS, which pose a series of challenges regarding their operation.

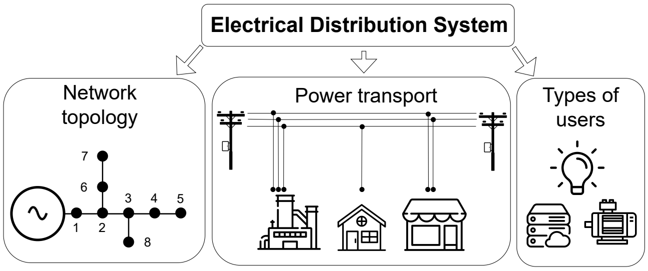

FIGURE 2: Challenges associated with electrical distribution systems

1) EDS topology

The topology of any system that connects different elements determines the most relevant operating aspects. In the case of EDS, topology impacts efficiency, reliability, and the cost of energy production. Regarding efficiency, a topology that minimizes the length of distribution lines can reduce energy losses due to conductor resistance. Similarly, a topology favoring redundancy and multiple feeding routes for loads results in greater reliability, and the implementation of one with fewer lines entails significant cost savings [29].

A large part of EDS worldwide are radial, which is due to the way in which the users are connected to it and to the economic advantages offered by this topology [30].

In a radial EDS, power flows in only one direction: from the central source or substation to the consumption points [31]. This results in a smaller infrastructure and, therefore, in lower implementation costs when compared to other topologies. However, as one moves away from the power source, the power flow decreases due to increased line resistance, which causes voltage drops and increases the system's power losses [32]. This challenge necessitates strategies to minimize energy losses while meeting the system's energy demands.

A meshed topology offers advantages in terms of system reliability, operation, and resilience, given its ability to distribute energy through multiple paths. However, this results in the need for more infrastructure, which increases implementation costs and makes it less attractive from an economic point of view [33].

2) Energy transport in an EDS

Most EPS use three-phase systems for the generation, transmission, and distribution of electric power, as these systems allow for the efficient transport of large amounts of energy over long distances and ensure a constant flow of energy [34]. In EDS, power is also transported through three-phase systems, but some users may be connected to single-phase grid sections, which is due to the nature of their electrical loads [35].

The ideal operation of a three-phase EDS implies a balance between its phases [36]. However, because users can be connected to the grid in different ways (single-phase, two-phase, or three-phase) as shown in Figure 3, the actual operation implies complications associated with the imbalance resulting from the direct interaction between the system and the users. This imbalance has an impact on the efficiency, reliability, and quality of the delivered power [37]. This poses a challenge regarding the proper operation of the system, which requires grid operators to develop strategies in order to guarantee the power supply and reduce energy losses while complying with quality standards.

In essence, a grid operator must ensure proper load planning. That is to say, they must evenly distribute loads among the phases of the system. However, effective planning must be accompanied by a continuous monitoring system with regard to the operating conditions of the EDS. This allows the grid operator to promptly detect imbalances and develop strategies to ensure EDS balance [38]. Some of these strategies could include load redistribution, the integration of DERs, or the implementation of advanced control and monitoring technologies [39], [40].

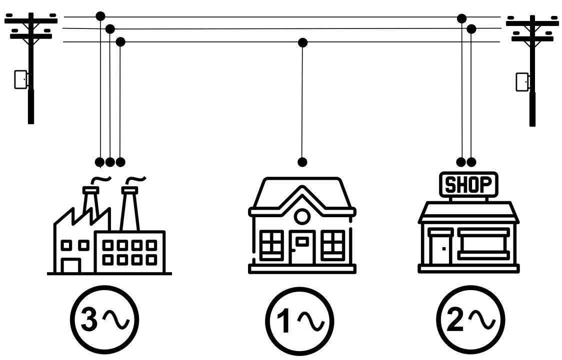

FIGURE 3: Types of connections to an EDS

3) The variability introduced by renewable resources

Over the past years, there has been a remarkable growth in the utilization of renewable energy sources to meet the energy needs of various regions. Among the leading technologies driving this growth are wind energy and photovoltaic (PV) solar energy. The latter enjoys widespread acceptance due to its availability in different parts of the world [41].

It is possible to represent the generation potential of PV sources through a curve over a time interval. For a typical day of operation, the curve has a characteristic shape, with a peak during daylight hours when solar radiation is most intense, declining towards the morning and evening. Similarly, it is possible to represent the energy consumption of a region as a function of its power demand during the same time interval [42]. In Figure 4, the characteristic behavior of both curves can be observed.

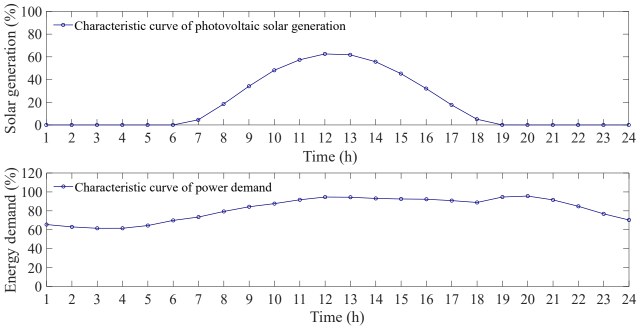

FIGURE 4: Characteristic power generation and demand curves

From the above, it is understood that there are times of the day when PV generation has a significant impact on system power levels, reducing reliance on conventional generators. While this can bring technical, economic, and environmental benefits, it also poses a series of challenges.

A clear example of the aforementioned can be seen in California (USA), a region with a high penetration of PV generation sources and with power demand levels that increase primarily in the late afternoon and early evening [43]. This means that, just at the end of the PV generation interval, the system's power demand increases significantly, requiring the extensive deployment of conventional generators to reach the required power levels. This can destabilize the system and cause operation failures. This phenomenon is known as the *California duck curve*, referring to the shape of the net power demand curve, which decreases during the peak PV injection hours at noon and suddenly rises towards the evening [44].

4) Types of users connected to EDS

An EDS must be able to serve users with diverse energy needs and demands. The way in which users connect to the grid, the type of loads they demand, and their consumption habits are characteristics that determine their impact on the operation of the system.

Loads can be resistive, capacitive, or inductive in nature, which may pose challenges related to power factor management and power quality control. The nonlinearity present in capacitive and inductive loads can cause harmonics and distortions in the current and voltage waveforms. All of the above contributes to increased current and voltage fluctuations, resulting in higher energy losses and reduced system reliability [45].

Users can be classified into different groups [46]. The first of these is known as the *residential user group* and comprises a high percentage of the total system demand. Residential users employ electrical energy to meet their daily needs, including lighting, heating, cooling, and entertainment. Although there may be capacitive and inductive loads, most of the devices in homes are resistive in nature. Most residential users are connected to the grid through single-phase network sections due to their low power demand and the nature of their needs. However, in buildings that house a significant number of residential users, three-phase connections may be required. It is important to note that the consumption habits of these users tend to vary over time [47].

Another important group of users corresponds to *commercial users*, who cover a wide variety of sectors. Similarly to residential users, their energy consumption can vary over time. These users employ energy to meet specific needs related to business operations, often requiring the system to be more efficient and reliable, as well as to provide power of better quality. The devices and machinery employed by these users tend to be mostly resistive and inductive and require a significant amount of power. Therefore, it is common for them to be connected to the grid through three-phase network sections [48].

One group that has a significant impact on the operation of EDS corresponds to *industrial users*. This group is characterized by a significant demand for electricity, which is used for productive purposes. It represents several sectors with specific and unique energy needs, and it is characterized by three-phase connections to the grid and by combining resistive, inductive, and capacitive loads. Naturally, this impacts the operation of the system [49].

Other grid-connected users, such as *institutional*, *agricultural*, *critical*, or *large* consumers may have different consumption needs and must satisfy different types of loads (resistive, inductive, and capacitive), requiring single- or three-phase connections to the grid. In conclusion, different users have different impacts on the operating aspects of EDS, which represents a challenge in terms of efficiency, reliability, and proper operation [50].

Finally, it is essential to highlight that the topology of the network, the means for transporting electric power, and the interaction with different user types pose a series of challenges to ensure the reliable and efficient operation of EDS. It is also important to mention that, in the operation of EPS, there are other characteristics that determine whether or not a given region can be connected to the system.

B. FACTORS INFLUENCING THE INTEGRATION OF TERRITORIES INTO LARGE EPS

Large EPS make it possible to meet the energy needs of different types of users, which are generally grouped in different territories [51]. As already mentioned, the transmission stage is in charge of carrying electrical energy from the generation site to the centers of mass consumption, which initiates the distribution stage. However, there are specific characteristics in each territory which determine the viability of the connection between both stages or subsystems.

The possibility of integrating a specific territory to a large EPS is determined by a series of factors that include topographic, social, economic, demographic, political, and cultural aspects [52]. Topographic conditions can sometimes make it difficult or very costly to install the infrastructure needed to connect the transmission stage to the distribution stage [53]. Similarly, social aspects such as the reluctance of inhabitants to the installation of infrastructure and conflicts related to land use often prevent the connection of a territory to large EPS [54].

Population density and distribution, together with the energy needs of a specific territory, may render the connection to large EPS unfeasible from an economic perspective [55]. In addition, it is important to note that political and regulatory aspects can influence the planning and implementation of electrical infrastructure projects, which in turn can determine whether or not a territory is to be connected to a large EPS [55]. When this is not feasible, the electrical system entrusted with meeting energy demands must operate independently, resulting in an isolated zone.

Isolated zones are established when it is impossible to connect a territory to a large EPS. Consequently, these areas do not have access to the energy generated and transmitted through large-scale infrastructures. Instead, these territories rely mostly on local sources, which are usually based on non-renewable energy [56].

Isolated areas are highly dependent on fossil fuels. Among the most commonly used are petroleum derivatives such as diesel, gasoline, kerosene, and fuel oil. This entails a negative environmental impact due to increased greenhouse gas emissions. In addition, this dependence makes energy production vulnerable to fuel price fluctuations. These types of areas tend to have a limited generation capacity, which can contribute to scenarios in which the total energy demand of the system is not met, especially at times of high demand. This can also lead to service intermittency.

EDS in isolated areas are also mostly built with radial topologies, given the low implementation costs [57]. The energy generated through local sources is distributed through systems of a three-phase nature and, in some sections of the network, under a single-phase configuration. As in connected areas, this type of topology poses some challenges related to the efficiency, reliability, and quality of the energy supplied through the system. Likewise, these networks serve users with different characteristics, behaviors, and needs, which turns EDS management into a problem of multiple variables, wherein technical, economic, and environmental aspects are crucial and have a significant impact on the quality of life and socioeconomic development of the communities that inhabit isolated areas. Therefore, strategies are required to adequately manage the energy needs of both grid-connected and isolated areas while ensuring a correct system operation.

C. STRATEGIES FOR MANAGING EDS IN INTERCONNECTED AND ISOLATED AREAS

During the last few years, different devices with an impact on the operating variables of EDS have been developed. As previously mentioned, these are called *distributed energy resources* (DERs). Through the correct integration and management of DERs, it is possible to obtain significant improvements in the technical, economic, and environmental aspects of the system, which is why network operators have focused their efforts on developing strategies to optimize the use of these devices. Figure 5 shows the main categories into which these devices can be grouped.

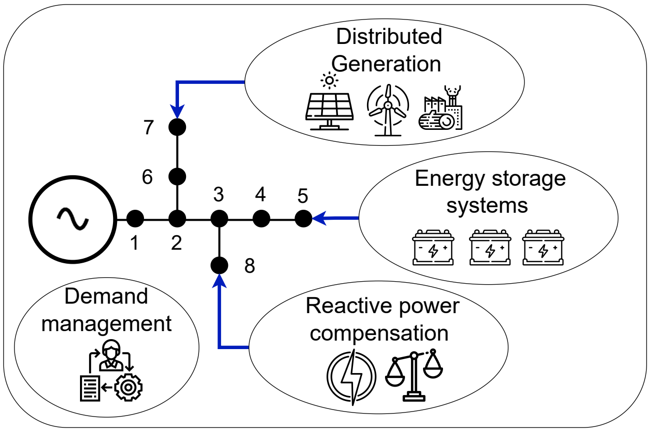

FIGURE 5: Main categories of distributed energy resources

1) Distributed generation devices

A distributed generation (DG) device enables power generation closer to the consumption points and reduces the dependence on the sources of large EPS. In addition, it can improve efficiency, reliability, and power quality by integrating with EDS. It also contributes to supplying the demand for electricity in territories that, due to their topographic, economic, social, cultural, and demographic characteristics, cannot be provided with electricity from large EPS [58]. Among the most widely used renewable energy sources for DG are solar, wind, hydro-, and biomass generators, each with special characteristics that make them relevant under some scenarios. Even though it is still possible to use sources that generate power from the use of fossil fuels, this has a negative impact on the economic and environmental aspects of the grid [59].

The integration of DG devices impacts the operating aspects of the grid, such as the nodal voltage profiles and the electrical current flowing through the system's distribution lines. This reduces energy losses and operating costs and contributes to reducing greenhouse gas emissions [60]. However, this integration poses multiple challenges, forcing grid operators to develop strategies aimed at optimizing the impact of these resources on EDS. Among the decision variables most widely explored in the literature are the location of the generators, their rated power, and the amount of energy they should inject [61].

One of the disadvantages of some DG sources, mainly those that use renewable energy resources, has to do with variations in power availability, which hinders the control of the generated energy and creates the need to incorporate devices that allow storing it at times of low availability and delivering it according to the energy demands of the system [62].

2) Battery energy storage systems

Battery energy storage systems (BESS) are of vital importance for strategies focused on improving the technical, economic, and environmental aspects of EDS. They complement the integration of DG devices, as they allow storing energy in times of excess generation and delivering it to end users when needed. This, in turn, is reflected in a greater power supply reliability and a significantly improved power quality. BESS allow controlling the voltage of the network, they help to efficiently manage the energy demand, and they reduce the congestion of the distribution lines. All this reduces a grid's energy losses and operating costs, and it improves the environmental aspects related to its operation [63].

Among the decision variables that have been most widely studied in the specialized literature and have a greater impact on EDS are the type of technology, the state of charge, and the location and sizing of batteries [24]. Therefore, the main challenge when integrating this type of devices lies in determining each of these variables, seeking the best technical, economic, and environmental impacts on the grid.

3) Reactive power compensation devices

The integration of different types of DERs contributes to the efficient and reliable operation of an EDS. Relevant aspects such as energy losses reduction, voltage profile improvement, and line current reduction are positively impacted by the proper management of the system's reactive power [64].

Reactive power plays a critical role in EDS. Although it is not useful on its own, it is essential for maintaining voltage levels, power quality, and system stability [65]. The introduction of active power through DG devices impacts every component of the system, affecting both its active and reactive power [65]. It is common to encounter situations where DG significantly alters the power balance of each component, resulting in energy losses and adversely affecting various operational aspects of the system, such as voltage levels and power quality [66].

A practical solution that has gained traction in recent years is the installation of reactive power compensation devices. These devices help to maintain the necessary power balance and improve the impacts related to the implementation of DG sources [67]. A variety of devices are currently being used, such as capacitor banks [68], static compensators [69], synchronous machines [70], and shunt transformers [71], among others. These devices differ in their ability to provide reactive power compensation to the grid. Capacitor banks are used to correct the power factor through fixed and constant compensation. They are suitable for applications where the reactive power demand is predictable [72].

On the other hand, static compensators provide dynamic reactive power control, allowing for variable and rapid compensation. They enable voltage control and system stabiliza-

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tion against rapid changes in load or operating conditions [73], [74].

Synchronous machines are electrical generators that can operate in both generation and motor modes. In their generation stage, they can provide reactive power to the system, helping to maintain voltage levels. However, their ability to provide reactive power is limited by the nominal characteristics of the generator and its excitation capacity [75].

Shunt transformers can provide reactive power compensation by adjusting the configuration of their windings, allowing them to absorb or supply reactive power according to the system's needs. This capability makes them versatile regarding power factor correction and voltage control [76].

The technology selected depends on the specific needs of each system and the characteristics of the network. Therefore, it is essential to consider relevant aspects such as the required power capacity, the necessary compensation speed, and flexibility and control capabilities to adapt to system parameters.

The integration and management of these devices have been the subject of multiple studies, the main objective of which is to optimize the operating aspects of EDS. Some decision variables extensively studied in the specialized literature include the location, sizing, and reactive power injection or absorption requirements [77].

It is also possible to combine different types of DERs to dynamically compensate the active and reactive power requirements of an EDS, as is evident in the case of PV-STATCOMs, or photovoltaic-based static synchronous converters. These systems are used in medium-voltage distribution networks to dynamically compensate for the active and reactive power generated by DG sources [78]. Control via PV-STATCOMs optimizes the use of PV inverter capacities and maximizes the utilization of the available solar energy. In addition, this allows them to function as a FACTS (flexible alternating current transmission systems), facilitating a dynamic reactive power exchange that dampens power oscillations in the EDS [79]. PV-STATCOMs provide variable reactive power from an alternate source, which adjusts to the load demand. Additionally, they reduce dependence on the conventional grid for both active and reactive power. Their main function is to act as voltage regulators and compensators for fluctuations in reactive power. These devices are designed to dynamically adjust the supply of reactive power to the loads connected at the point of common connection in a grid-connected PV system [80], [81].

BESS can also be integrated with reactive power compensation devices. In this case, the STATCOM device, being a voltage source converter, can supply reactive power to the system, injecting or absorbing it as needed. Likewise, BESS can store or release power, either active or reactive. The integration of these two technologies allows for a proper control of system voltage and frequency profiles, thus impacting system efficiency and reliability [82].

4) Demand management systems

Particularly, if energy management by DGs and BESS cannot ensure continuity of service or achieve the objectives set by the grid operator, it is possible to consider the disconnection of non-critical loads in the system. This disconnection must be carried out carefully, without exceeding the minimum demand limits established for critical loads within the system [83].

Finally, it is important to highlight that the integration and management of DERs allows designing strategies aimed at improving technical conditions, such as energy losses, voltage profiles, and current flows. It also improves economic aspects, such as investment and operating costs, and it has an impact on environmental aspects, *e.g.*, the reduction of greenhouse gas emissions. However, DERs involve different decision variables that, added to the operating constraints associated with EDS, turn their integration and management into a multi-variable problem of high complexity.

D. MATHEMATICAL COMPLEXITY IN THE INTEGRATION AND MANAGEMENT OF DERS WITHIN EDS

The integration and management of DERs in EDS is difficult to solve from a mathematical point of view. The electrical variables of a system of this nature exhibit nonlinear behaviors, and some relationships used to determine their operation are stochastic [84]. In this context, optimization problems exhibit non-convexities that prevent determining whether the solutions found are in fact the best ones. Likewise, DG, storage, and reactive power compensation devices incorporate decision variables representing the DERs' mode of operation [85].

Non-convexities arise due to the presence of multiple non-linear constraints and objective functions, which may stem from various sources such as the interactions between different components of the electrical system, DER operating constraints, and system dynamics [86].

The interaction between DERs and the rest of the electrical system can generate non-convexities. For instance, the presence of multiple generation sources and the temporal and spatial variability of renewable generation can lead to nonlinear power balance constraints. These constraints can create non-convex regions in the solution space, complicating the design of optimal operation strategies [87].

1) Nature of the variables

Any strategies for integrating and managing DERs must incorporate variables of a non-linear and non-convex nature which represent the electrical behavior of the system. These can be binary, discrete, or continuous.

Many DERs exhibit nonlinear behaviors, which can be attributed to effects such as component variability and operating constraints. The accurate modeling of these nonlinearities is a complex issue. Additionally, analyzing the impact of integrating DERs into a EDS requires evaluating the power flow of the system, which, given the nonlinear nature of the electrical variables involved, can result in equations that are difficult to solve and may require the use of numerical methods.

To determine the type of technology, location, sizing, and power injection level of each device, a mathematical model must include variables of binary and continuous nature [88]. In the case of DG, the location of the generators is represented through discrete variables indicating the nodes of the system in which they should be installed. Likewise, to determine the power injection level and the nominal size of these generators, variables of a continuous nature are used. As for BESS, the type of technology is represented by binary variables, the location of the devices by discrete variables, and both the state of charge and the nominal size by continuous variables [89]. Similarly, the location of reactive power compensation devices is represented through discrete variables, and aspects such as their nominal size and the amount of power to be injected or absorbed by them are represented using continuous variables [90].

Finally, the integration and management of DERs is a mixed-integer nonlinear linear programming (MINLP) problem that, when represented through a mathematical model, is highly complex to solve.

2) Mathematical formulation

The mathematical formulation necessary to represent the operation model of a distribution system in a context of DER integration considers objective functions that seek to optimize various aspects. In the specialized literature, these aspects are technical [91], economic [92], and environmental [93] in nature.

Regarding the technical objective functions used, one of the most studied aspects is the minimization of energy losses ($\min E_{\text{loss}}$), which is mathematically formulated as shown in Equation (1).

$$min\, E_{loss} = \sum_{h\in\mathcal{H}}\sum_{l\in\mathcal{L}} R_l I_l^2 \Delta h \tag{1}$$

In the given expression, R_l represents the resistance of line l; I_l denotes the magnitude of the current flowing through line l; and Δh corresponds to an interval in which the electrical variables remain constant. It is crucial to note that $\mathcal{H}$ spans all time periods, while $\mathcal{L}$ encompasses all the lines in the EDS.

Similarly, among the economic objectives of further analysis, it is possible to find the reduction of operating costs ($min\ E_{cost}$). These costs are represented in the purchase of energy from conventional generation sources (f_1) and in the costs of DER operation and maintenance (f_2), as can be seen in Equation (2).

$$min\, E_{cost} = f_1 + f_2 \tag{2}$$

To calculate f_1 and f_2, factors such as C_{kWh} and $\mathrm{C}_{O\&M}$ are used to represent the average cost of acquiring energy from the conventional grid and the operation and maintenance costs of DERs, respectively. This is shown in Equations (3) and (4).

$$f_1 = \mathrm{C}_{kWh}\left(\sum_{h\in\mathcal{H}}\sum_{i\in\mathcal{N}} P_{i,h}^{cs}\Delta h\right) \tag{3}$$

$$f_2 = \mathrm{C}_{O\&M}\left(\sum_{h\in\mathcal{H}}\sum_{i\in\mathcal{N}} P_{i,h}^{DERs}\Delta h\right) \tag{4}$$

In Equations (3) and (4), Δh represents the period during which the electrical variables remain constant. In addition, $\mathcal{N}$ represents all nodes, and $\mathcal{H}$ all periods of EDS operation. Likewise, $P_{i,h}^{cs}$ and $P_{i,h}^{DERs}$ represent the power injected by the conventional generators and DERs (respectively) connected to node i during the time period h.

From an environmental point of view, the minimization of CO_2 emissions ($min\ E_{CO_2}$) has attracted great interest in recent years [26]. In this vein, a CO_2 emissions factor associated with conventional power generation sources (FE_{cs}) is used, as shown in Equation (5).

$$min\, E_{CO_2} = FE_{cs}\left(\sum_{h\in\mathcal{H}}\sum_{i\in\mathcal{N}} P_{i,h}^{cs}\Delta h\right) \tag{5}$$

It is also important to keep in mind that the system has a number of operating constraints that must be mathematically modeled in order to analyze its behavior in the face of DER integration. One of the most studied corresponds to the nodal active and reactive power balances, as shown in Equations (6) and (7).

$$P_{i,h}^{cs} + P_{i,h}^{DERs} - P_{i,h}^{d} = V_{i,h}\sum_{j\in\mathcal{N}} Y_{ij}\, V_{j,h}\, \mathrm{Cos}\left(\theta_{i,h} - \theta_{j,h} - \varphi_{ij}\right), \begin{Bmatrix}\forall i\in\mathcal{N}\\ \forall h\in\mathcal{H}\end{Bmatrix}, \tag{6}$$

$$q_{i,h}^{cs} + q_{i,h}^{DERs} - Q_{i,h}^{d} = V_{i,h}\sum_{j\in\mathcal{N}} Y_{ij}\, V_{j,h}\, \mathrm{Cos}\left(\theta_{i,h} - \theta_{j,h} - \varphi_{ij}\right), \begin{Bmatrix}\forall i\in\mathcal{N}\\ \forall h\in\mathcal{H}\end{Bmatrix}, \tag{7}$$

In these equations, $P_{i,h}^{cs}$ and $q_{i,h}^{cs}$ represent the active and reactive power supplied by conventional sources connected to node i during period h, while $P_{i,h}^{d}$ and $Q_{i,h}^{d}$ indicate the active and reactive power demanded at node i during the same period. Furthermore, $P_{i,h}^{DERs}$ and $q_{i,h}^{DERs}$ represent the active and reactive power injected at node i by DERs during period h. The terms $V_{i,h}$ and $V_{j,h}$ denote the magnitude of the voltage at nodes i and j (respectively) during time h, while $\theta_{i,h}$ and $\theta_{j,h}$ express the voltage angle at nodes i and j for the same period. Additionally, Y_{ij} is the admittance magnitude of the line connecting nodes i and j, and φ_{ij} represents the angle of the admittance of that line.

The limits regarding active and reactive power in conventional generators and DERs are also commonly taken into account and can be represented through Inequalities (8), (9), (10), and (11).

$$P_i^{cs,min} \leq P_{i,h}^{cs} \leq P_i^{cs,max}, \begin{Bmatrix}\forall i\in\mathcal{N}\\ \forall h\in\mathcal{H}\end{Bmatrix} \tag{8}$$

$$Q_i^{cs,min} \leq Q_{i,h}^{cs} \leq Q_i^{cs,max}, \begin{Bmatrix} \forall i \in \mathcal{N} \\ \forall h \in \mathcal{H} \end{Bmatrix} \tag{9}$$

$$P_i^{DERs,min} \leq P_{i,h}^{DERs} \leq P_i^{DERs,max}, \begin{Bmatrix} \forall i \in \mathcal{N} \\ \forall h \in \mathcal{H} \end{Bmatrix} \tag{10}$$

$$Q_i^{DERs,min} \leq Q_{i,h}^{DERs} \leq Q_i^{DERs,max}, \begin{Bmatrix} \forall i \in \mathcal{N} \\ \forall h \in \mathcal{H} \end{Bmatrix} \tag{11}$$

In these inequalities, $P_{i,h}^{cs}$ and $Q_{i,h}^{cs}$ represent the active and reactive power bought from or injected by the conventional generator at node i during the time interval h. Likewise, $P_i^{cs,min}$ and $P_i^{cs,max}$ denote the minimum and maximum active power assigned to the conventional generator at node i, while $Q_i^{cs,min}$ and $Q_i^{cs,max}$ represent the minimum and maximum reactive power assigned to the same generator. Additionally, $P_i^{DERs,min}$ and $P_i^{DERs,max}$ are the minimum and maximum active power assigned to the DERs according to system needs. $Q_i^{DERs,min}$ and $Q_i^{DERs,max}$ are the minimum and maximum reactive power assigned to the DERs.

Other important constraints include nodal voltage limits, represented by Inequality (12), and current limits, as shown by Inequality (13) [26].

$$V_i^{min} \leq V_{i,h} \leq V_i^{max}, \begin{Bmatrix} \forall i \in \mathcal{N} \\ \forall h \in \mathcal{H} \end{Bmatrix} \tag{12}$$

$$I_{l,h} \leq I_h^{max}, \begin{Bmatrix} \forall l \in \mathcal{L} \\ \forall h \in \mathcal{H} \end{Bmatrix} \tag{13}$$

Here, Vi^{min} and Vi^{max} are the minimum and maximum voltages allowed, respectively. Moreover, Il, h denotes the current flowing through line l during the time period h, and Ih^{max} is the maximum current allowed for each line.

In addition to these constraints, the integration model for different types of DERs may have constraints associated with the operation of each device, such as the type of technology and load and discharge percentages (in the case of BESS), as well as constraints related to the economic feasibility of integrating and managing these devices [24].

To the best of our knowledge, there is currently no DER integration model that allows including all the constraints associated with the operation of each device. Moreover, only a few research works address two or more objective functions simultaneously [94]–[96], which poses a challenge due to the mathematical complexity involved in the multi-variable integration of such a problem.

Finally, it is important to highlight that, while optimizing a single objective may be beneficial for EDS operation, it is essential to note that the real challenges faced by grid operators require methodological approaches that address the simultaneous optimization of multiple aspects. However, the main complexity of multi-objective optimization lies in the potential existence of conflicts between the functions to be optimized. This forces grid operators to develop strategies allowing to optimize their operation according to their specific interests and to apply expert judgment with the purpose of selecting the best option [97].

E. ASSESSING THE IMPACT OF DERS ON EDS

The mathematical problem regarding the operation of EDS is difficult to solve due to the nature of these systems and their associated variables. A good operation strategy for this type of system must have tools to evaluate the electrical conditions of the network under different scenarios. Likewise, they should allow quantifying the impact of DER installation on important operating aspects. Power flow analysis is an effective tool that provides relevant information about the operation of a system at a given time. It is used to describe the energy transfer between different nodes and is based on Kirchhoff's laws. Its mathematical model relates impedances, currents, voltages, and power in the different elements of the network [98].

1) Power flow

The power flow problem allows for a diagnosis of the system based on the power demanded and generated within it while using the parameters of the electrical system (bus types and location, as well as data on the lines and the constant impedances at the nodes) [99]. By analyzing initial data such as the power delivered by the generators and the power demanded by the consumers, the voltages at each of the system's nodes are calculated for a permanent regime. Likewise, the active and reactive power flows in each of the system components (lines, transformers, reactors, and capacitors) are calculated in order to guarantee a global power balance. The power flow problem allows verifying the operating conditions of an EPS, for which two stages are employed. The first one seeks to determine the complex voltages of all nodes by solving the system of nonlinear equations representing the problem. The second one uses the results from the first stage and, by means of routine calculations, determines the active and reactive power flows and losses of the elements, as well as other technical, economic, and environmental indicators required by the network operator [100].

The nodal voltage method is fundamental for analyzing the power flow of distribution systems. Through the magnitude and angle of the voltage at each node, it allows determining some relevant variables associated with the operation of the system. To perform this analysis, a set of algebraic equations is taken into account, which employ six variables of interest to characterize electrical behavior (voltage magnitude, voltage angle, active power generated, active power demanded, reactive power generated, and reactive power demanded) depending on the type of node evaluated – some of these variables may be known. In distribution systems, two types of nodes are analyzed. First, there is the slack node, considered to be the strongest in the system and characterized by its ability to compensate for active and reactive power oscillations, as it can control the voltage in the system. The second type of node is the PQ node, to which the loads are connected.

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For this node, the active and reactive power consumption is known. The goal of this analysis is to determine the magnitude and angle of the voltage. In addition, only energy consumptions are considered [99].

The main objective of power flow analysis is to determine the magnitude and angle of the voltage present at each of the nodes. With these data, and through the mathematical formulation that represents the power flow problem, actions can be proposed to control important aspects of the distribution system. The power flow is obtained from the net power injected (S). Therefore, the contribution of each node to the system must be taken into account. This contribution is positive if it comes from a generation node (S_g), negative if it comes from a load or a demand node (S_d), or zero if it is associated with a pass-through node without generation or consumption. Equation (14) represents the net power injected.

$$S = S_g - S_d \tag{14}$$

The power input at node k (represented by S_k) is determined by the voltage (V_k) and the conjugate current ($\overline{I_k}$) according to Equation (15).

$$S_k = V_{k*}\overline{I_k} \tag{15}$$

To simplify the mathematical model, it is convenient for the current to not be conjugate. This results in the expression shown in Equation (16).

$$\overline{S_k} = \overline{V_k} I_k \tag{16}$$

Using the concept of nodal admittance (Y), it is possible to correlate the currents and voltages of each node in matrix form, as demonstrated in Equation (17).

$$\begin{bmatrix} I_1 \\ I_k \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{k1} & Y_{kk} & Y_{kn} \\ Y_{n1} & Y_{nk} & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_k \\ V_n \end{bmatrix} \tag{17}$$

The current at node k (I_k) can be found through Equation (18).

$$I_k = \sum_{j=1}^{n} Y_{kj^*} V_j \tag{18}$$

Finally, by replacing the above value into Equation (16), the general formulation of the power flow problem is obtained, as seen in Equation (19).

$$\overline{S_k} = \overline{V_k} \sum_{j=1}^{n} Y_{kj^*} V_j \tag{19}$$

The expression shown above has real and imaginary terms and is composed of non-linear equations that make it difficult to solve. Therefore, it is common to find different mathematical methodologies that allow determining the power flow through each node via computational tools. These methodologies are compared with a view to optimize some relevant factors, such as data processing times, repeatability, and convergence.

2) Power flow evaluation methods

The focus of this paper is on radial networks, as they are most commonly used in designing distribution power systems. These networks have a single slack node, for which the voltage is known, and the remainder are demand nodes with an unknown voltage. This allows separating the system into components associating generation buses with generation buses (Y_{gg}), generation uses with demand buses (Y_{gd}), demand buses with generation buses (Y_{dg}), and demand buses with demand buses (Y_{dd}), as shown in Equation (20).

$$\begin{bmatrix} Y_{gg} & Y_{gd} \\ Y_{dg} & Y_{dd} \end{bmatrix} \begin{bmatrix} V_g \\ V_d \end{bmatrix} = \begin{bmatrix} I_g \\ I_d \end{bmatrix} \tag{20}$$

From the expression shown above, and considering Equation (19), it is possible to express this relationship through Equation (21).

$$\overline{S}_g - \overline{S}_d = \text{Diag}(\overline{V})(Y_{\text{bus}})V \tag{21}$$

However, taking advantage of the aforementioned characteristics of radial grids, this expression can be divided into one equation for the slack node, *i.e.*, Equation (22), and another one for the demand nodes, *i.e.*, Equation (23).

$$\overline{S}_g = \text{Diag}(\overline{V}_g)(Y_{gg}\overline{V}_g + Y_{gd}\overline{V}_d) \tag{22}$$

$$-\overline{S}_d = \text{Diag}(\overline{V}_d)(Y_{dg}\overline{V}_g + Y_{dd}\overline{V}_d) \tag{23}$$

Equation (22) is linear, so there are no major complications when solving it. However, Equation (23) exhibits a non-linear behavior, since the demand voltages are not known.

In the specialized literature, several methods are used to solve the power flow problem, which can be adapted to analyze both single- and three-phase systems. In the case of the latter, more variables must be taken into account. This greater mathematical complexity leads to an increase in computational efforts and inevitably results in considerably increased processing times. Among the traditional approaches are some numerical methods such as the Gauss-Seidel and the Newton-Raphson techniques, which use iterative processes to find the solution to the problem [26]. In in each iteration of the Gauss-Seidel method, the values of the stresses are sequentially updated, gradually converging to the solution. The above makes this method suitable for determining the power flow in small EDS [101]. On the other hand, in the Newton-Raphson method, the variables are not updated sequentially, and each iteration involves a recalculation through the use of a Jacobian matrix that includes their partial derivatives, leading to a faster convergence in comparison with the Gauss-Seidel method [102]. This technique is suitable for solving the power flow of large EDS. However, the solution of the Jacobian matrix requires a larger number of simultaneous computations, which makes its implementation more computationally intensive [103].

Another, more recent method to solve the power flow is the successive approximations method (SA). This method is based on the Gauss-Seidel approach, with the main difference being the possibility of dealing with the variables directly in their complex form, which eliminates the need to perform transformations that ultimately result in a greater mathematical complexity and, therefore, in greater computational challenges [104].

Other alternatives can be found in the literature, such as the iterative sweeping method and the triangular method, which may be useful depending on the specific characteristics of each system [105].

The iterative sweeping method is similar to the SA method, and its mathematical formulation does not require derivatives to obtain the variables. However, the nodal voltages are distinguished from the voltages in the branches of the system. The directions of the currents flowing through the lines are assumed, and their effects are represented by a node-branch incidence matrix. During the iterative process, all variables are updated simultaneously from their most recent values, which prevents the dependence between variables in each iteration. This method may be appropriate for analyzing large systems, but its convergence depends on a good estimation of the initial parameters [105]. As for the triangular method, its mathematical formulation is derivative-free and, like the iterative sweeping method, it differentiates between nodal and branch voltages. The main difference lies in the use of a triangular matrix representing the nodal currents carried by each of the branches. Its processing times are reduced because some components of the mathematical formulation are only calculated once and not in each iteration [105].

3) Relevant aspects in power flow assessment

Power flow assessment in EDS under DER installation scenarios allows determining the impacts associated with the integration of each device. This evaluation usually requires a significant number of iterations depending on the size of the system and the number of variables integrated into the mathematical model. To solve the flows, computational tools are used which, depending on the complexity of the model, demand specific computational loads and processing times [106].

A good integration and management strategy must ensure computational efficiency in evaluating power flows, and it must also obtain solutions in reasonable times. This is important, considering that the time used to solve the power flows increases exponentially with respect to the number of variables in the problem [106].

Another important point of the evaluation has to do with the repeatability of the obtained solutions, which indicates their quality and reliability. In addition, this helps network operators to make better decisions according to the behavior of the system [106].

Finally, it can be stated that the challenges associated with the operation of EDS and the fact that systems may or may not be connected to large EPS necessitate strategies integrating DERs in both grid-connected and isolated areas. These strategies require tools such as power flow analysis, which allows evaluating the operating conditions of the grid under different scenarios.

4) Impact on the operating aspects the EDS

DERs improve various operating aspects of EDS, with an impact on their technical, economic, and environmental conditions. Each DER has unique characteristics and different impacts.

DG devices can inject active power at different points within the grid, which reduces the need to transport energy from conventional generation sources to the load. This reduces energy losses, improves the voltage profile at each node, and reduces the electric current flowing through the system. All this is reflected in a higher efficiency, a more reliable system, and a higher-quality power supply [107].

BESS complement the operation of DG devices by storing energy in times of excess generation and releasing it according to system demands. This, in addition to reducing energy losses, improving voltage profiles, and reducing current flows, allows for a proper system control and affects the operating frequency, which translates into a greater reliability, efficiency, and quality of the power supply [108].

Lastly, reactive power compensation devices can inject or absorb reactive power depending on the needs of the network. For power factors affected by capacitive components, the main objective should be to inject reactive power. Although it is not common in EDS, scenarios may arise where this contribution is required. On the contrary, for EDS with power factors impacted by inductive components, the interest shifts towards the absorption of reactive power [109]. In both scenarios, the aforementioned devices have an impact on important system variables, *e.g*, the power factor, the voltage profiles at the nodes, and the current flowing through the lines. This is reflected in the efficiency, reliability, and quality of the power supplied by the EDS [22].

F. APPROACHES FOUND IN THE SPECIALIZED LITERATURE FOR THE ENERGY MANAGEMENT OF DERS IN EDS

During the last few years, different strategies have been developed in order to manage DERs in EDS through different optimization methods. These strategies seek to improve technical aspects such as energy losses, voltage profiles, and current flows. They also address economic aspects, as is the case of investment and operating costs, and consider environmental aspects such as greenhouse gas emissions reduction. The most explored approaches are analytical, numerical, heuristic, and metaheuristic in nature. It is also common to find a combination between some of these, which may be convenient depending on the characteristics of the problem to be solved [26].

1) Analytical approaches

Analytical approaches are based on theoretical analysis through mathematical models representing the relationships between the electrical components of the system, which allows obtaining exact solutions when the proposed model is linear and convex. However, one may find that DER integration and management problems are mostly non-linear and non-convex, which would demand an excessive computational load and prohibitive solution times. Among the most commonly used optimization methods for the analysis of DERs are linear programming techniques, useful for optimizing the location and sizing of generators, and quadratic optimization techniques, which allow optimizing the use of reactive power compensation devices. Nonlinear optimization techniques are also widely used and contribute to the analysis of nonlinear constraints within the system, such as generation limits, nodal current limits, and current limits across distribution lines [110].

2) Numerical approaches

Numerical methods allow finding solutions that are reliable and of good quality. In addition, they help to solve optimization problems of a non-linear and non-convex nature, which are typical of EDS. They allow the optimization model to include important equality and inequality constraints in analyzing the feasibility of solutions. Their reliability depends on the accuracy of the data entered into the model, and their convergence is sensitive to the initial conditions of the problem [111]. It is important to note that they are appropriate for addressing optimization problems in systems of different sizes. However, the processing times and computational load required to find the solutions is proportional to the number of variables and constraints in the problem, which, for large EDS, can lead to prohibitive times. Among the most commonly used approaches are the Gauss-Seidel and Newton-Raphson methods, useful for analyzing optimal power flow and network stability problems [102].

3) Heuristic approaches

Heuristic methods, on the other hand, are based on simple and intuitive rules and do not use precise mathematical calculations, which directly impacts aspects such as computational efforts and processing times. However, they do not guarantee that the solution found is indeed the best one, as they may get stuck in local optima [112]. They are appropriate for solving optimization problems that combine a large number of variables and require a simplistic exploration and exploitation of the solution space. They usually converge quickly, finding acceptable solutions in reasonable periods of time. Because these types of techniques are used with practical and specialized approaches, they do not employ recognized algorithms, and, on the contrary, they use the knowledge of a given problem to propose algorithms that adapt to the characteristics of each problem [112].

4) Metaheuristic approaches

Metaheuristic methods share some similarities with heuristic ones. However, metaheuristic methods are solved exactly by finding approximations to the global optimal solution. In addition, the greatest difference lies in their efficiency. Metaheuristic techniques are characterized by the fact that they are based on mathematical and structured principles, which allows them to approach different optimization problems in a systematic way. They are appropriate for solving combinatorial problems of a non-linear and non-convex nature, which is typical of large-scale EDS. Given their stochastic nature, it cannot be guaranteed that, through this type of method, any of the solutions found will be the best one. Nevertheless, they allow finding solutions of very good quality under a moderate computational load and in acceptable processing times. Among the most widely used techniques is the particle swarm optimization (PSO) algorithm, which allows determining the location and sizing of devices and, in some cases, the type of technology to be used. It is also common to find the use of genetic algorithms (GAs) to analyze the behavior of EDS. In general, different metaheuristic optimization techniques are employed in the specialized literature to address the optimization problem regarding EDS operation in the context of DER installation. However, the optimization technique selected will depend on the type of problem to be solved and on the nature of its variables [113].

III. ANALYSIS OF THE ADVANCES MADE IN THE SPECIALIZED LITERATURE

Considering the growing number of publications on this topic, a search for articles published since 2018 was performed in different databases, *i.e.*, ScienceDirect, IEEE, and Scopus. For this search, keywords such as DG, BESS, reactive power compensation, optimization techniques, and siting and sizing were used, among others.

Figure 6 shows the recent increase in the number of studies on the topic.

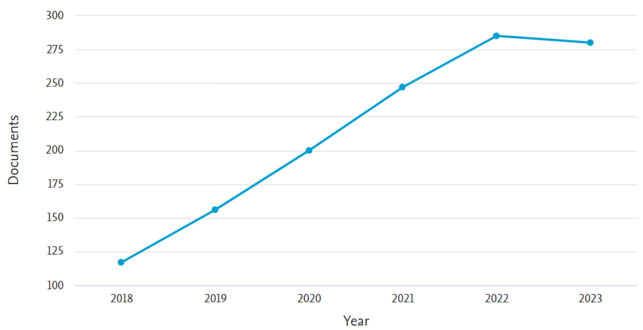

FIGURE 6: Related publications per year

Figure 7 shows the distribution of subject areas with regard to related publications.

It can be seen how many authors seek to improve the operation of EDS through the integration and management of a single DER technology. However, strategies that simultaneously integrate and manage DG, BESS, and compensation devices have sparked great interest in recent years, and most of the reported works seek to optimize scenarios involving the integration of two or more technologies. In addition, the reported works also differ in the way they an-

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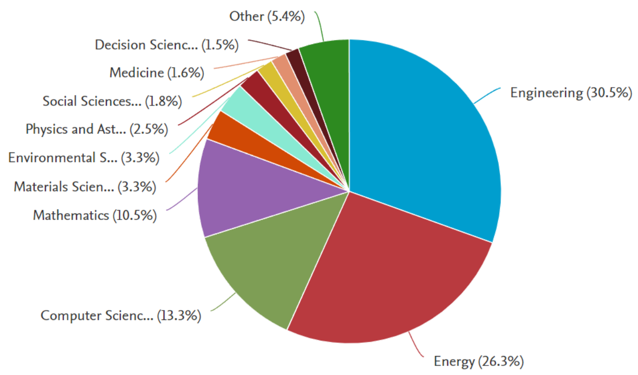

FIGURE 7: Related publications per subject area

alyze power distribution. Some studies propose optimization models based on the analysis of single-phase equivalents. This type of equivalent simplifies the analysis by ignoring the imbalances inherent to the operation of EDS. This means that the improvements obtained do not represent solutions to the real problems. On the other hand, there are studies that use models analyzing the problem while considering a three-phase operation, which results in useful tools for network operators.

A. STRATEGIES ADDRESSING THE INTEGRATION AND MANAGEMENT OF A SINGLE TYPE OF DERS

This section presents some of the works reported in the specialized literature which contain strategies for the integration and management of a single type of DER. For each work, the type of technology, the decision variables, the objective functions, and some relevant aspects are described, such as test scenarios, their corresponding equivalent (single- or three-phase), and the main findings.

- The research conducted by Purlu *et al.* presents a strategy to determine the optimal power factor, the best locations, and the best power injection level for different types of DG [114]. Using the PSO technique, the authors define some operating aspects of the system as the optimization objectives: the annual reduction of energy losses and the improvement of each node's voltage profiles. To validate their results, they use the 33-node test system, which, through an analysis based on the single-phase equivalent, allows quantifying the improvements obtained by the proposed algorithm, as well as comparing the results against those of other algorithms. Among the most relevant results of this research, the authors highlight energy losses reductions of 39.8% with the installation of PV generators and of 64.3% with the implementation of wind turbines. However, energy storage and compensation devices are not taken into account, and the economic and environmental aspects inherent to this type of project are not analyzed.
- The work by Tianming *et al.* [115] proposes a strategy to optimize the operating aspects of EDS with DG devices. This is done through the integration of a BESS and the proper placement and sizing of storage devices. To this effect, the authors employ an improved version of the non-dominated sorting genetic algorithm II (NSGA-II), which focuses on reducing the energy losses of the system and improving the voltage profiles of each node. To validate the results of the proposed strategy, the authors use a 33-node, single-phase radial test system. The implemented optimization technique was compared against the traditional NSGA-II algorithm and the multi-objective particle swarm optimization (MOPSO) algorithm.
  Among the most relevant results reported by the authors, an improved solution repeatability stands out in comparison with the NSGA-II and MOPSO techniques. However, the authors do not provide information on the processing times required by each algorithm. In addition, the base case involves DG devices with fixed location and sizing. If not optimized, these aspects condition the improvements obtained. Moreover, reactive power compensation devices are not included, which, as in the case of DG, could improve the impacts on the studied EDS. Finally, it is important to highlight that the analysis was conducted using a single-phase equivalent, which, although useful for this type of problem, does not represent the real behavior of a three-phase EDS.
- Nezhad *et al.* developed a strategy to manage DG units via a fuzzy decision-making method (FDMM) [94]. They used the multi-objective improved manta ray foraging optimization (MOIMRFO) algorithm to determine the correct placement and sizing of each device in order to minimize energy losses and improve voltage profiles. This strategy was implemented in a 33-node three-phase unbalanced test system under variable generation and load conditions, which allowed quantifying the improvements obtained and comparing them against those of other optimization techniques reported in the literature. Among the most relevant results, the authors highlight a 9.8% reduction in energy losses, a 25% reduction in the nodal voltage imbalance, and a 12% improvement regarding unserved energy. However, this work does not include energy storage and compensation devices, it does not analyze the repeatability of the solutions, and it does not quantify the processing times required by each solution. In addition, the analysis fails to include the relevant economic and environmental aspects of this type of projects.
- The work presented by Nassef *et al.* [116] proposes a methodology to reduce energy losses through the optimal allocation of biomass DG units in EDS. Using a modified version of the hunger game search (HGS) algorithm, the authors propose the location, sizing, and power factor of the DG sources as decision variables in a single-objective optimization environment. The 33-, 69-, and 119-node test systems are used to validate this methodology in single-phase balanced systems.

Among the main findings, the authors report energy losses reductions of 94.49% for the 33-node system, 97.68% for the 69-node system, and 88.79% for the 119-node system. However, the published results do not allow determining the repeatability or the processing times required. In addition, when performing an analysis under a single-phase equivalent, the line imbalances corresponding to the real operation of these systems are not considered. It is important to highlight that the study is limited to a technical analysis and does not include the review of economic and environmental aspects. Furthermore, it only focuses on the integration of DG sources and does not analyze the possibility of installing other types of DER such as BESS and D-STATCOMs.

- The research carried out by Cortés *et al.* [24] seeks to reduce energy losses and minimize CO_2 emissions by correctly selecting the technology, location, and sizing of BESS in microgrids with the presence of DG devices. Through the formulation of a MINLP model, the authors use a master-slave methodology based on optimization algorithms, such as the Chu & Beasley genetic algorithm (PCBGA) and the vortex search algorithm (VSA). In addition, using the SA method to evaluate the power flow, the results of this strategy are validated on the 33-node test system. Among the main findings, the authors highlight the improvement of the microgrid's operating aspects and the mitigation of CO_2 emissions, reducing dependence on traditional sources that use fossil fuels for power generation.
  This analysis used a single-phase equivalent; it failed to consider a relevant aspect of real operation: the imbalance of the three-phase distribution lines. It is important to mention that, as the evaluation was performed under a scenario where the DG sources had already been installed, the technical, economic, and environmental aspects associated with the location and sizing of this technology were not optimized. In addition, the authors highlight the need for future work that integrates other optimization techniques while addressing the problem from a multi-objective perspective, thus allowing to simultaneously optimize different aspects.
- Cikan *et al.* [117] propose a methodology to determine the location, size, connection type, and power factor of three different technologies related to the installation of DG installation in unbalanced three-phase systems. This methodology is based on the equilibrium optimization (EO) algorithm, which is inspired by the behavior of animals in nature. The EO algorithm delivers candidate variables to a three-phase backward and forward unbalanced power flow (UBFLF) evaluator, which allows determining the impact of each proposed solution. The authors use the 123-node IEEE system as a test scenario for their methodology. This test feeder has been barely explored in the specialized literature.
  This work was modeled using the MATLAB environment and simulated in Simulink, IEEE PES, and OpenDSS. For comparison, the authors used six optimization algorithms that have been widely explored in the literature and applied to the research problem. These were implemented under the same conditions as the EO algorithm and helped to demonstrate the improvements obtained by the proposed method in terms of processing times, repeatability, and some statistical variables.
  Finally, as the main results of their research, the authors present a decrease in energy losses of 92.59% and improvements in voltage profiles when installing nine distributed generators. This, in comparison with the base case. However, they do not address the current imbalances in the distribution system lines, an inherent aspect of DG systems. Validations under scenarios with variable generation and power demand were also not carried out, which is fundamental in studying DG systems. In addition, the scope of this research was limited to single-objective optimization, focusing on the operating aspects of the network. This hindered the evaluation of impacts on economic and environmental aspects.
- Mohan *et al.* focus on improving the operating conditions of BESS in the presence of renewable DG [118]. Through the correct placement and sizing of BESS, the authors suggest improving aspects such as nodal voltage profiles and system power losses. To this effect, they use an optimization algorithm called the *water cycle algorithm* (WCA), which, after being evaluated in test systems with 33 and 43 single-phase nodes, shows improvements with respect to the base case in relevant aspects such as the deviation of voltage levels at each node and the reduction of power losses. The authors also perform an analysis of the processing times required by this strategy, which, in comparison with techniques such as PSO and the gravity search optimization algorithm (GSA), takes less time to find the solutions to the problem. However, the single-phase approach of the analysis does not allow considering the typical imbalances of real operation. In addition, this research does not allow quantifying the economic and environmental impact of this type of strategies, implying the need for future works that integrate different objective functions into a multi-objective optimization model within the framework of a three-phase analysis.
- The work presented by Ali *et al.* [119] proposes a methodology to improve the operating conditions of EDS through the correct integration of DG units. To this effect, the authors use a hybrid optimization algorithm that combines the qualities of the PSO algorithm and the sine-cosine algorithm (SCO). In a multi-objective optimization environment, the authors suggest improving key aspects such as the energy losses, voltage profiles, and line imbalances of three-phase distribution systems. To validate the efficiency of the proposed methodology, the authors used test systems of 13, 37, and 123 nodes,

and they compared the results obtained against the PSO and SCO algorithms, which were used separately. The authors report reductions of 89% in energy losses, 21% in the imbalance index, and 70% in the voltage profile index for large-scale systems. However, they do not evaluate the repeatability and processing times of the solutions obtained. Energy storage and reactive power compensation devices are not included either, which would allow for an integral management of the network. It is important to mention that the technical analysis performed does not allow quantifying the improvements obtained in economic and environmental aspects transversal to this type of integration.

In summary, each of the previously proposed strategies suggests decision variables tailored to the characteristics of each scenario. Notably, the locations and power injection levels of different types of DERs are considered, given their potential impact on the operating aspects of the EDS. For instance, installing a DG source at a specific node may reduce the need to transport energy over long distances, consequently decreasing associated transmission losses. Additionally, this device can reduce the system's reliance on conventional generation, impacting operating costs and polluting gas emissions. Another decision variable of interest is the power factor, given the multiple benefits of optimizing it within a system, including reduced line currents and improved voltage profiles at each node.

In addition to the above, it is important to note that several authors utilize widely explored optimization techniques. Some examples include algorithms such as PSO, MOIMRFO, HGS, PCBGA, NSGA-II, and FDMM, among others. Thes algorithms differ from each other primarily in the way they explore and exploit the solution space. This defines the evolution of possible solutions and impacts their convergence, determining relevant aspects such as processing times and computational load.

The proposed strategies address the operational challenges of the EDS, such as energy losses, voltage profile variations, and high line loads. To this effect, they utilize mathematical models that represent the behavior of the EDS in the context of DERs integration. Furthermore, through different optimization algorithms, the best scenarios for DERs integration and operation are defined. In this vein, power flow validation tools are employed, allowing to understand the impacts associated with the implementation of the proposed solution.

It is important to mention the limitations of some studies, as they do not integrate different types of DERs simultaneously. This is relevant, considering that these devices often complement each other and can achieve significant improvements by working together. The interaction between different types of DERs can address challenges such as system stability and the need for dynamic response to variations in EDS operation. For example, the intermittency associated with generation from renewable energy sources can be mitigated through energy storage systems. These systems enable storing power during intervals when the generation exceeds the demand and supplying it during periods when the demand surpasses the generated power. This contributes to enhancing system stability and allows for a greater DERs penetration in current EDS [120].

It is also important to highlight that some studies solely focus on improving a single objective, overlooking the opportunity to optimize other relevant aspects that are also impacted by the integration and operation of DERs. Additionally, some methodologies use equivalent single-phase circuits to model the behavior of the EDS, which may limit the accuracy of the results, as most EDS operate with three-phase systems for energy transportation.

Ultimately, it is essential to emphasize that test systems are an important validation tool that helps the scientific community to quantify the improvements obtained, especially when the studied strategies cannot be validated in real situations. However, key aspects such as the equivalent circuit used, the quality of the solutions obtained, the processing times required, and the type of optimization performed are of vital importance to determine the reproducibility of simulations in real EDS.

It is common for different authors to compare their results based on the quantitative reduction of each objective function value and the impact of decision variables on each element of a test system. To this effect, it is essential to conduct an evaluation of the initial conditions of the test system, which will allow for such comparison. Additionally, it is possible to compare different methodologies through statistical analysis, in order to determine the repeatability of the solutions and the processing times required to obtain them.

Table 1 presents a summary of the related works and their main characteristics. It shows how technical objective functions have been the subject of different works, demonstrating their relevance. However, economic and environmental aspects have been scarcely explored, which implies the need to propose future works that address the integration of DERs in scenarios aimed at optimizing these aspects. Likewise, there is a clear need for strategies that operate in a multi-objective context and are adjusted to the current needs of EDS. Finally, it is important to note that some authors propose future studies integrating different types of DERs.

B. STRATEGIES THAT ADDRESS THE SIMULTANEOUS INTEGRATION AND MANAGEMENT OF DIFFERENT TYPES OF DERS

Some works in the literature have developed strategies aimed at simultaneously integrating and managing different types of DERs, some of which are described below.

- The work presented by Campolina *et al.* [121] proposes a strategy to determine the best location of DG devices and capacitor banks (CBs) in EDS. To this effect, the authors use a GA entrusted with improving operating conditions and minimizing energy losses in unbalanced three-phase distribution systems. The proposed optimization algorithm is responsible for determining the

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TABLE 1: Related works in the specialized literature and their characteristics

Ref.	DER type	Objective function	Strategy	Solution technique used	Test system	Equivalent circuit	Variable conditions	Comparison with other techniques	Statistical analysis
[114]	DG	Technical	Single-objective	PSO	33 nodes	Single-phase	Yes	Yes	Yes
[115]	BESS	Technical	Multi-objective	NSGA-II	33 nodes	Single-phase	No	Yes	No
[94]	DG	Technical	Multi-objective	MOIMRFO	33 nodes	Three-phase	Yes	Yes	No
[116]	DG	Technical	Single-objective	HGS	33, 69, and 119 nodes	Single-phase	Yes	Yes	Yes
[24]	BESS	Technical, economic, and environmental	Single-objective	PCBGA and VSA	33 nodes	Single-phase	Yes	Yes	Yes
[117]	DG	technical	Single-objective	EO and UBFLF	123 nodes	Three-phase	No	Yes	Yes
[118]	BESS	Technical	Single-objective	WCA	33 and 43 nodes	Single-phase	No	Yes	No
[119]	DG	Technical	Multi-objective	PSO and SCO	13, 37, and 123 nodes	Three-phase	Yes	No	No

nodes of the EDS where the installation of DG and CBs yields the best operational impacts, considering factors such as voltage profiles, line load percentage, and system stability.

In addition, they propose a methodology to reduce the search space by analyzing the initial population of the algorithm. To validate the effectiveness of their strategy, they use test systems of 4, 7, 37 and 123 nodes in the context of variable generation and demand. When comparing their results against those of different works using algorithms such as PSO and Montecarlo simulation, they report a reduction of 60% in the computation times required for each solution. However, by focusing on the improvements made to the operation of the system, they fail to consider the economic and environmental impacts of the proposed strategy. They also do not take energy storage systems into account and do not include decision variables such as the power injection of the devices in the optimization model. These authors propose future work dealing with strategies to optimize aspects such as line imbalances and nodal voltage profiles.

- Leng *et al.* propose a strategy for coordinated DER operation that is based on a stochastic programming model (SPM) [122]. The main objective of this strategy is to minimize energy losses and improve voltage profiles in three-phase EDS within the framework of single-objective optimization. To this effect, decision variables such as power injection by storage devices and the selection of different types of DG are employed.

  The 34-node test system was used to validate the research results. Among the most relevant results is the creation of a realistic strategy that enables the joint optimization of technical aspects with reasonable operating costs. To demonstrate this, the authors use some strategies reported in the literature for the sake of comparison. However, they do not quantify the improvements obtained with respect to the base case or consider the locations of the devices as decision variables in the optimization model. In addition, they do not analyze the environmental impacts associated with the implementation of the strategy and fail to present a statistical analysis of their results.
- Grisales *et al.* present a strategy for battery management in urban and rural distribution networks under a scenario of variable DG and power consumption [123]. Using an improved version of the VSA, the authors propose a single-objective optimization model in which different operating constraints are considered and technical, economic, and environmental aspects of the network are improved.

  To validate the effectiveness of this strategy, the authors employ test systems of 27 and 33 nodes adapted to the characteristic generation and demand conditions of two regions in Colombia, and, using a single-phase equivalent, they analyze the operation of the system before and after the implementation of their proposal. Among the main results are the quality of the solutions obtained in comparison with those of other algorithms, as well as significant improvements in reducing energy losses and CO_2 emissions. Reductions of 4.29% and 7.4% in energy losses were observed in the urban and rural scenarios. Additionally, reductions of 0.18% and 0.08% in CO_2 emissions were recorded, respectively.

  However, by analyzing a single-phase equivalent, the authors fail to consider the behavior of a real three-phase distribution system, and therefore the line imbalance inherent to it. It is important to highlight that a multi-objective analysis of the proposed strategy could provide a useful tool for decision-making by network operators.
- The work by Ray *et al.* [124] proposes a strategy to determine the optimal allocation of active and reactive power devices in three-phase distribution networks, with the objective of improving voltage profiles and reducing energy losses. This strategy uses the SCO to establish, under different variable load scenarios, the most appropriate power injection or absorption.

  The authors use the 25-node test system to quantify the improvements obtained, highlighting the enhanced voltage profiles of each node, as well as reductions in energy losses between 78.18% and 80.09% for different load levels. However, it is important to point out some limitations of this study, such as the absence of a statistical analysis to determine the quality of the solutions obtained. Likewise, the processing times required to find the solutions, a fundamental aspect in this type of strategy, are not indicated. In addition, there is no economic or environmental analysis of the impacts associated with the implementation of this approach.

- The research conducted by Radosavljević *et al.* [125] presents a methodology for the optimal allocation of active and reactive power in EDS with the presence of single-phase DG devices and BESS. The authors combine PSO with sigmoid-based acceleration coefficients (PSOS) and a chaotic gravity search algorithm (CGSA) within a single-objective optimization environment with varying generation and demand conditions. The main objective of this methodology is to reduce the losses and costs associated with the purchase of energy from traditional sources.
  To carry out this study, the authors implemented the proposed methodology in the three-phase 13-node test system, comparing their results against those of other optimization techniques such as PSO and a GA. A 22% reduction in daily energy losses and enhanced nodal voltage profiles were observed. However, it is important to note some limitations regarding their analysis. First, the research does not include an evaluation of the environmental impacts associated with reduced energy purchasing from conventional sources, which is a relevant consideration in the current context of energy sustainability. In addition, the proposed model does not regard the current imbalance in each line as a constraint, an aspect of vital importance to represent the real operation of EDS. No statistical analysis is performed to validate the quality of the solutions obtained, nor are details provided with regard to processing times.
- Kumar *et al.* present a strategy for the optimal integration of DG and energy storage systems in power distribution grids [95]. This strategy is based on a multi-objective optimization model, whose decision variables include the location and sizing of different DERs. The authors use a multi-objective optimization algorithm based on the velocity butterfly method (MOVBOA). The main objective of this strategy is to minimize energy losses and improve stress profiles in various test scenarios. The performance of the proposed strategy was validated on 33-, 69-, and 118-node single-phase test systems with variable demand and probabilistic generation. Significant improvements in voltage profiles and reductions in energy losses were observed in the three test systems. The reductions in energy losses were 80%, 91%, and 62% for the 33, 69, and 118-node systems, respectively.
  It is important to highlight that this work by Kumar *et al.* lacks a statistical analysis to demonstrate the repeatability of the solutions obtained. In addition, it does not provide information on the processing times employed by the algorithms. Furthermore, the analysis is carried out using the single-phase equivalent of the different test systems. Although these tools are useful for evaluating optimization strategies, they do not allow addressing the aspects inherent to the actual operation of three-phase EDS, such as line imbalances.
- Kandasamy *et al.* [126] propose a distributed static synchronous compensation (D-STATCOM) and DG device integration strategy for radial three-phase EDS. Using multi-objective optimization and under time-varying load conditions, their strategy uses the enhanced artificial bee colony (EABC) algorithm to determine the best combination, placement, and power injection of DG and D-STATCOM units.
  The proposed mathematical model uses a multi-objective function aiming for power losses reductions, current flow reductions, and nodal voltage profile improvements. To validate the effectiveness of the proposed strategy, test systems of 13 and 33 nodes are used. With respect to the base case, the authors report a 43% reduction in energy losses for the 13-node unbalanced network, as well as 64% for the 33-node system. In addition, they highlight the impacts on the nodal voltage profiles and load reductions in the lines of the test systems. However, they do not consider the effect of their strategy on current balance, nor do they analyze the economic and environmental impacts derived from the implementation of DG and D-STATCOMs.
  It is important to mention that this work does not present any results obtained using other methodologies, which would certainly be useful to quantify the improvements made. In addition, the analysis of the solutions lacks relevant information, such as processing times.
- Tahiliani *et al.* conducted a research focused on reducing energy losses and improving the operating aspects of three-phase power distribution grids [127]. To this effect, they proposed a methodology based on the atom search optimization (ASO) algorithm, which allows managing the power injected by DG and D-STATCOM devices in variable load scenarios. This methodology was validated using the 25-node test system, and improvements in voltage levels and reductions in power losses were reported for several scenarios. However, it is important to note that this study lacks crucial information that would allow validating the repeatability of the solutions and evaluating their processing times. Furthermore, as variable generation scenarios are not included, it is not possible to analyze the uncertainty associated with the energy sources used in the study. Finally, this research does not address the environmental impacts of DER management.
- The work presented by Fardinfar *et al.* [69] proposes a strategy to determine the optimal sizing and placement of DG and DSTATCOM devices in three-phase distribution power grids. Through a hybrid optimization technique that combines the PSO algorithm and Monte Carlo (MC) algorithm, the strategy allows improving the voltage profiles at each node and reducing the energy losses associated with transport. Under a single-objective optimization environment, the authors

implemented the proposed strategy in a real distribution system located in Kerman, southwestern Iran. The authors highlight, as one of the main contributions of the proposed strategy, the development of a tool that helps network operators with the design and planning of radial distribution networks.
It is important to point out that the study lacks a statistical analysis to determine the quality of the solutions obtained and their corresponding processing times. In addition, it does not evaluate the economic and environmental conditions before and after the installation of the DERs, which are fundamental aspects in this type of project.

- In their research work, Giridhar *et al.* present a hybrid power system composed of DG, BESS, and D-STATCOM devices [128]. These devices aim to improve energy losses in grid-connected systems and ensure an independent supply for isolated areas. Regarding the first objective, DG sources are exclusively integrated to improve the operating aspects of networks that rely on a conventional feeder. In the second objective, through the simultaneous integration of the three devices, the aim is to reduce dependence on conventional generation sources. This, until energy independence is achieved. For both cases, the research proposes an optimization strategy whose decision variables correspond to the siting and sizing of the devices.
In a context of single-objective optimization, the mayfly algorithm (MOA) used allows finding appropriate values, which reduce the active power losses by 47.37% and the reactive power losses by 42.89% in a system with 33 single-phase nodes. Furthermore, according to the authors, this strategy is effective in ensuring the supply of electricity to isolated areas. However, the analysis performed lacks information to estimate the repeatability of the solutions and their processing times. In addition, as the system is analyzed using a single-phase equivalent, the effects of line imbalance, which is typical of real distribution systems, are not taken into account. It is important to point out that this work focused on the technical aspects of the system and did not consider any economic and environmental aspects.
- The work presented by Sharma *et al.* [96] proposes an operation strategy for different types of DERs which is aimed at minimizing energy losses and energy purchasing from the grid. Through the multi-objective NSGA-II, the authors elaborate a methodology that allows determining the optimal power dispatch of batteries under variable demand and generation scenarios and in the coordinated presence of wind sources and shunt CBs.
This strategy was implemented in the 33-node single-phase test system and a real 108-node distribution system. Among the main findings, the authors highlight reductions of 77.97% in the energy losses and 65.11% in the operating costs of the 108-node system. However, there is no analysis of the environmental impacts associated with this research. Moreover, this work does not allow determining the impact of the methodology on operating aspects of the network such as line loads, and it does not present the processing times required by each solution. Moreover, as it evaluates the power flow using a single-phase equivalent, it does not consider the line imbalance of a real three-phase distribution system.

Finally, it is important to highlight that, both in scenarios using only one type of DER and in cases involving the simultaneous integration of two or more, the works reported herein take the location, sizing, and operation of different devices as decision variables. In addition, variables such as the type of technology become especially relevant given the specific characteristics of each system.

Table 2 presents a summary of related works that integrate two or more types of DERs. It shows how different authors have proposed the simultaneous integration of various devices in variable demand and generation scenarios. However, as was made evident in the previous subsection, economic and environmental aspects have been little explored, as well as the use of multi-objective optimization. All of the above highlights the need to carry out future work that simultaneously integrates DG, energy storage systems, and reactive power compensation devices under variable demand and generation conditions, in addition to analyzing scenarios where technical, economic, and environmental aspects are simultaneously optimized. It is also important to note that these works should focus on three-phase test systems representing the real operation of EDS.

It is important to mention that, as far as could be evidenced, most of the reported works elaborate optimization models aimed at improving technical and economic aspects. However, environmental aspects are often left unexplored. In addition, some works lack statistical analyses, scenarios with variable conditions, and comparisons with other techniques. Multi-objective approaches have also been little explored in this type of multi-variable problem and, more specifically, in the integration of different DERs – some authors even propose it as future work.

IV. CONCLUSIONS AND FUTURE WORK

After reviewing the state of the art, it is evident that the search for strategies to improve the operating aspects of EDS has sparked great interest, and that work in this field is being done on different fronts. This is reflected in the development of new technologies that seek to mitigate the existing inefficiencies of traditional EDS and reduce their dependence on conventional generation sources. Likewise, new technologies also make it possible to meet the energy needs of areas that cannot be connected to large-scale EPS.

Different authors have proposed strategies to optimize the technical, economic, and environmental aspects of installing DERs in EDS in both grid-connected and isolated areas. However, since this is a combinatorial problem, the complexity of the mathematical model representing the operation of the system is often directly proportional to the number of

TABLE 2: Related studies in the specialized literature and their characteristics

Ref.	DER type	Objective function	Strategy	Solution technique	Test system	Equivalent circuit	Variable conditions	Comparison with other techniques	Statistical analysis
[121]	DG and BC	Technical	Single-objective	GA	4, 7, 37, and 123 nodes	Three-phase	Yes	Yes	Yes
[122]	DG and BESS	Technical	Single-objective	MPE	34 nodes	Three-phase	No	Yes	No
[123]	BESS and DG	Technical, economic, and environmental	Single-objective	VSA	27 and 33 nodes	Single-phase	Yes	Yes	Yes
[124]	DG and D-STATCOM	Technical	Single-objective	SCO	25 nodes	Three-phase	Yes	No	No
[125]	DG and BESS	Technical and economic	Single-objective	PSOS and CGSA	13 nodes	Three-phase	Yes	Yes	No
[95]	DG and BESS	Technical	Multi-objective	MOVBOA	33, 69, and 118 nodes	Single-phase	Yes	No	No
[126]	DG and D-STATCOM	Technical	Multi-objective	EABC	13 and 33 nodes	Three-phase	Yes	No	No
[127]	DG and D-STATCOM	Technical	Single-objective	ASO	25 nodes	Three-phase	Yes	No	No
[69]	DG and D-STATCOM	Technical	Single-objective	PSO and MC	N/A	Three-phase	No	No	No
[128]	DG, BESS, and D-STATCOM	Technical	Single-objective	MOA	33 nodes	Single-phase	Yes	Yes	No
[96]	DG and BC	Technical and economic	Multi-objective	NSGA-II	33 and 108 nodes	Single-phase	Yes	Yes	No

variables to be optimized. Therefore, the simultaneous integration and management of DG, BESS, and reactive power compensation technologies has been little explored. Some authors resort to relaxing these problems through single-phase equivalents, and they approach the analysis from a single-objective perspective, sometimes failing to consider the aforementioned aspects – some works even propose future research aimed at including some of them.

It is for all the above that there is a need to design integration and management strategies for DERs which simultaneously consider DG, BESS, and reactive power compensation devices using multi-objective optimization while identifying their impact on the technical, economic, and environmental aspects of three-phase EDS under conditions of variable generation and demand. All this should be done with adequate computational loads to obtain solutions of good quality in decent processing times.

These strategies will allow for an adequate management of the resources and energy needs of different regions, with particular effects on isolated areas, where they can contribute to ensuring a stable, efficient, and high-quality electrical supply, thus improving local communities' quality of life and contributing to social development through an energy transition that responds to local development plans.

Based on the above, the main contribution of this article is a comprehensive analysis of the fundamental challenges related to the operation of three-phase AC distribution systems, highlighting the strategies employed by grid operators to ensure a reliable delivery of electric power. Additionally, a critical evaluation of various strategies based on intelligent algorithms aimed at improving the impact of DERs implementation is carried out. This analysis and review provide a complete insight into the technical and operational aspects involved in the integration of such resources, which can serve as a guide for future research and practices in the field of electrical distribution systems.

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