Photovoltaic Distributed Generators with an Energy Storage System

Subjects: Engineering, Industrial
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Disruptive events, such as the winter storm of 2021 that left 40 million people in the U.S. without power, have revealed the potential danger of societal dependence on centralized energy sources. Localized energy grids (called microgrids (MGs)) can help add energy reliability and independence by using distributed generators (DGs) with photovoltaic (PV) energy sources and energy storage systems (ESSs). Such MGs can independently energize critical energy demand nodes (DNs) when isolated from the primary grid with renewable energy. The optimal sizes and assignments of PVDG/ESS units to the DNs during outages are crucial to increasing energy reliability.

Keywords: resilient power grid ; distributed generation ; renewable energy ; genetic algorithm

1. Introduction

There are various modern examples where unforeseen disruptive events deprive people of access to electrical power. These events can cause anything from minor inconveniences to situations (leading to mortal danger). Since the 2000s, there has been a drastic increase in weather-related power outages (affecting more than 50,000 customers [1][2]). One recent example is the winter storm that hit the lower 48 U.S. states in 2021, leaving 4 million people without electricity. A distributed generation microgrid (MG) can help make energy access more reliable and resilient to unforeseen disruptions while increasing energy independence. A properly configured MG can be run as the only energy source (island mode) or as extra energy to power all or some of an area's critical energy demand nodes (DNs). DNs, such as hospitals, fire stations, and grocery stores, can be prioritized during disruptions to maintain safety and comfort. MGs, in these situations, must fully or partially power all necessary DNs with minimal investments, operations, and maintenance costs. MGs with PVDG sources are promising but require additional considerations and equipment to utilize their potential fully. In an island mode situation where the MG is expected to provide emergency power, which is the focus of the work, these issues are critical to optimal solutions.

According to a report by the National Renewable Energy Laboratory [1], photovoltaic distributed generation (PVDG) systems could supply electricity during grid outages resulting from extreme weather or other emergencies. In order to take advantage of this capability, the systems must be designed with energy uncertainties in mind and combined with other technologies, such as energy storage systems (ESSs). DGs that utilize renewable energy sources (RESs) can help provide environmentally friendly energy sources but cause unique problems. First, PVDG energy output ties directly to environmental conditions, such as the amount of solar radiation an area receives and the area's current sky conditions (cloudiness). Thus, energy output from the PVDG is intermittent, so there is a need to regulate the power received by DNs to see a consistent voltage profile even when solar resources are low. Second, high energy output from the PVDG can pose issues. Excess unused energy can cause reverse power flow (RPF) in systems with renewable energy sources. If the system generates more power than the DN requires, issues in the primary energy grid, such as loss of voltage control, increased dangers from short circuits, and degradation of the reliability of protective systems, can occur [3][4][5]. Thus the appropriate sizes or capacities of PVDG systems are crucial to help minimize these issues.

ESSs can help control voltage fluctuations and the RPF that RESs can cause by storing and discharging energy as needed. The appropriately chosen ESS capacity is key to ensuring that the ESS is optimally utilized. Too large of a capacity leads to wasted monetary resources due to unused capacity; too small, and there may not be enough storage to help mitigate potential RPF or provide enough backup energy. However, adding the appropriately sized ESS will only improve conditions with appropriate charging strategies. A good charging strategy must respond with power when the system is at low output, be reactive to the intermittent production of RESs, and be able to store excess energy at the appropriate times [6]. Charging unnecessarily when the system is at a low output or discharging when the system is at a high output will only amplify RES-related problems. As more renewable sources become a part of the energy grid, assignments, sizing, and storage management strategies become increasingly important.

Due to the varied capacity sizes, possible locations, and different charging strategies of DGPV/ESS systems finding optimal solutions can be problematic and computationally expensive. In addition, a feasible solution must consider the uncertain nature of the environmental conditions upon which the RESs depend on. Therefore, researchers are active in the optimal DG/ESS placement and sizing (ODGSP) problems, as well as ESS energy management. Many have sought to solve these problems using various techniques, including purely numeric, heuristic, machine learning [7], and simulation [8].

2. Optimal Sizing and Distributed Generation Placement

There has been a lot of research on ODGSP. Analytical, numerical, and heuristic methods, such as GAs, are the most common [7]. A review of the methods used to find optimal solutions to the ODGSP, conducted by [7], found that heuristic methods are usually robust and provide near-optimal solutions for significantly complex ODGSP problems. For example, [9] utilized GAs and particle swarm optimization (PSO) algorithms to obtain the optimal allocation and size of a PVDG system. Their goal was to reduce the total power losses and enhance voltage and frequency profiles using an objective to minimize these factors. The simulation results indicate that the PSO algorithm performs better than GA in terms of speed of convergence, power loss reduction, and grid quality improvement for the chosen objective. They also show that variable load consumption curves and changing weather conditions can affect the determination of the PVDG optimal position, capacity, and grid security, indicating the importance of modeling weather conditions to gain feasible solutions. Similarly, the works by Hengsritawat et al. [8] used the Monte Carlo simulation and statistical data to quantify the stochastic and probabilistic nature of PVDG energy production. Hengsritawat et al. showed that when finding optimal solutions to the ODGSP in a test case in Thailand, the inclusion of factors, such as background harmonic distortion, change the optimal solution and, thus, are essential considerations when designing an optimal PVDG MG. The authors of the book *Artificial Intelligence and Renewables* [10] used GA-derived ODGSP solutions to improve the live voltage stability index (LVSI). Other GA-based hybrid algorithms, such as the GA-GSF (genetic algorithm with generating scaling factor), have been employed to optimize DG sizing and placement. GA-GSF-based optimization of line capacities in systems (to minimize locational marginal prices (LMPs) by finding optimal sizing and placements) has been successful. It allows for identifying a network's weaknesses to help avoid line congestion that increases LMP [11][12]. The work by [13] utilizes the manta ray foraging optimization (MRFO) to optimize the ODGSP using a multi-objective function. These works show that GAs and other heuristic methods are commonly utilized to solve the ODGSP problem, with varying optimization goals. Results indicate that various heuristic algorithms are robust and reliable tools for these optimization problems.

3. Distributed Energy Storage Placement (DEP) and Management

Similarly, research has been conducted on the optimal sizing and placement of ESSs. Reference [14] performed a critical review on ESS planning covering ESS sizing and modeling algorithms. Their work provided a critical one-stop overview of one hundred and four methods in six categories of optimization techniques. The research presented various pros and cons of the different methods, including analytical, heuristic, and hybrid approaches. They concluded that while all have their strengths and weaknesses, the most promising strategies are found through hybrids of individual methods. In [15], the authors presented an algorithm to determine the optimal installation placement and sizing of an ESS for a virtual multi-slack (VMS) operation based on a power sensitivity analysis in a stand-alone successful microgrid. In [16], the authors looked at problems associated with deploying an intermittent, unpredictable, and uncontrollable solar photovoltaic PVDG that could be feasibly solved with a battery ESS (BESS) by optimizing the available capacity, increasing reliability, and reducing system losses. The mentioned research projects show that the common understanding of the importance of ESS to distributed generation is still being explored, and various analytical, heuristic, and hybrid tools have proven successful. As mentioned, proper utilization requires an appropriate charging strategy when using ESS with PV systems, and the next section looks at research related to this subject.

4. ESS: Storage Management and Optimal Charging Strategies

Much of the research on energy management methodologies for ESSs focus on using EVs (electric vehicles) as a part of the system. The possible economic, ecological, and social benefits support the rapid diffusion of grid-connected MGs; however, economic feasibility still stands as the primary goal of commercial MGs [17]. In [18], the authors shows that—similar to the conclusion found by [14]—hybrid optimization methods for energy storage and management of a DG/ESS system where EVs are present can minimize costs. They found optimal configurations by utilizing real-time electricity prices, real-time calculation of PV power based on solar radiance, and an extensive system simulation. However, in [17], the authors found that the bidirectional charging strategy (using BESS to charge EVs and using EVs to store and supply energy at peak demand times) may not pay off in the long run. Researchers are also looking into the optimal management of ESSs to buffer charging infrastructures for smart cities. In [19], the authors focused on maximizing demand with increased EV presence at a minimal cost. They modeled the charging station network and energy storage system, showing potential savings of 20–36% for energy storage development. These research examples show that the ESS management aspect of the DG/ESS system is essential to utilizing PVDG systems and is expanding to include the growing number of EVs in today's market. The mentioned studies discuss standard capabilities that the addition of ESS to PVDG can impart, such as providing power during peak demand times and maximizing demand met. These factors are essential when attempting to run a PVDG/ESS system in island mode, which is the focus of this work.

5. Island Mode Mg Analysis

The capability of a DG/ESS system to provide power in island mode is also a hot topic of research. According to Georgilakis and Hatziargyriou [7], the intentional islanding of DG MGs increases the economic competitiveness of DGs and improves reliability across the board. The authors of Satheesh Kumar and Immanuel Selvakumar [20] looked into the analysis and optimization for islanded DG and ESS systems intending to maximize power point tracking and power flow management. In Abdelgawad [21], the authors utilized a random forest hybrid technique with an embedded system and a numerical/analytic approach to maximize the efficiency of solar energy harvesting systems, supplying an MG. In Dhundhara and Verma [22], the authors researched utilizing other ESS technologies, such as hydro energy storage for reliable microgrid systems. In Wang et al. [23], the authors formulated the ODGSP as a mixed-integer program (MIP) considering the probabilistic nature of DG outputs and load consumption, wherein the costs were minimized. In an islanded situation, profits were maximized for MG. Other researchers have also sought to minimize the costs of an islanded ESS-based MG. In Hesaroor and Das [24], the authors sought for solutions to minimize the running cost of a BESS MG by a heuristic method that exploited the price difference in time of a usage tariff scenario. The researchers utilized incremental cost data to find optimal sizing solutions for the ESSs among five different cases.

The studies mentioned above show that optimizing MG utilizing DG/ESS systems in island mode is essential as the penetration of renewable energy increases and the need for more resilient energy systems rises. The mentioned works take varying resolution levels when modeling the MG and focus on various objectives from minimizing costs to controlling power quality and providing energy management strategies and combinations of the former. This work takes a high-level approach to model the MG, excluding discussions of the power system factors related to power quality control and the degradation of the PV/ESS units as an initial step in building a more physically accurate model of an island mode MG. The current model is meant to explore the optimization performance, ability for DN prioritization, and feasibility of the energy management strategies produced by the methods described. This work seeks to utilize simulation and heuristics-based optimization, considering uncertainties from the intermittent nature and changing load demands of renewable energy generation to find solutions based on the environmental conditions of specific areas. Through the use of historical data about a region's average PV outputs throughout the day and statistics about the sky conditions of the area, and realistic approximations of a set of DG/ESS units can be simulated. The algorithm can then compare the performance of each proposed solution according to a predefined set of constraints and metrics. This description describes the perfect framework for a GA-based solution. The simulation allows for quantifying the stochastic environmental conditions and, subsequently, stochastic PV output. The GA allows for a directed search through the solution space with the researchers' defined objective of maximizing the energy demands met while minimizing costs under a set budget. The simulation and GA methods of finding optimal solutions involve performing tasks in a manner that more mathematical methods may find intractable over "larger" horizons. The following section will provide a formal description of this work's problem, a mathematical description of the objective that the GA solution seeks to optimize, and the constraints of the simulated system.

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