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Intelligent Integration and Operation of Distributed Generation Sources in Unbalanced Three-Phase Distribution Systems

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Abstract: The increase in energy consumption poses significant challenges for current Electrical Distribution Systems (EDS). Distributed Generation (DG) helps reinforce these systems by improving their operating conditions. However, optimizing key factors such as DG source placement and power injection is necessary to maximize the benefits. This paper proposes a methodology for the optimal integration and operation of DG sources in unbalanced three-phase EDS, using the particle swarm optimization (PSO) algorithm and the successive approximations method (SA). Results are validated on a 25-node test system adapted to dynamic demand and energy generation conditions, achieving a 34.5% reduction in system energy losses.

Keywords: PSO, DG, Optimization, EDS, Energy losses, Successive approximations.

Introduction

In recent years, global population growth has led to increased energy consumption. While traditional power systems have met much of this demand, they now face significant challenges. Most of these challenges arise during the distribution stage, where energy is delivered to end-users, known as the Electrical Distribution Systems (EDS). Each user presents distinct characteristics regarding the nature of their loads and energy consumption levels, contributing to the unbalanced operation of EDS and affecting system reliability and efficiency (Gallegos et al., 2024).

The integration of Distributed Generation (DG) sources near end-use points has emerged as a solution to existing issues within EDS. This integration not only helps meet growing energy demand but also improves the system's operational conditions. However, to achieve significant operational improvements, it is essential to accurately determine the location of each DG source and the power they should inject at specific time intervals. This requires that DG sources be integrated and operated intelligently to maximize their benefits within the EDS (Loji et al., 2023).

The specialized literature proposes methodologies for the intelligent integration and operation of DG sources aimed at improving the technical, economic, and environmental conditions of the grid. These methodologies address the mathematical complexity inherent in EDS under DG integration scenarios, which stems from the diversity of loads and the emergence of nonlinear and non-convex variables in the system's power flow. Additionally, since each EDS node can serve as a candidate for DG installation, discrete variables are required, while the level of power injection, which varies according to each source’s nominal power, necessitates the use of continuous variables (Gajardo-Aspee et al., 2024). These methodologies utilize analytical, numerical, heuristic, metaheuristic, or combined methods. Among them, metaheuristic optimization methods stand out as they yield high-quality solutions within relatively short computational times (Guzman-Henao et al., 2023).

Several authors have used benchmark systems reported in the literature to validate their methodologies' results, modeling system operation through a single-phase equivalent circuit that facilitates load flow evaluation. For instance, the work presented in (Pawar et al., 2024) proposes the installation of DG sources using the Squirrel Search Algorithm-Assisted Cat Swarm Optimization (SSI-CS) algorithm to determine DG sources' locations and sizes. Furthermore, to validate the results and the economic improvements achieved, the IEEE 33-bus test system was used. In (Majeed et al., 2024), the authors proposed a methodology to reduce energy losses by optimizing the placement of DG sources within an IEEE 33-bus test system, employing a combination of the Newton-Raphson (NR) method and Particle Swarm Optimization (PSO). Similarly, in (Nogueira et al., 2023) developed a methodology utilizing PSO and Symbiotic Organisms Search (SOS) algorithms with the main objective of improving the technical conditions of a 33-bus test system.

Although representing an EDS using a single-phase equivalent circuit is useful for analyzing system operations, it does not accurately reflect its real behavior. Therefore, methodologies that incorporate power flow evaluations considering the unbalanced three-phase operation of these networks are required. These methodologies should be assessed under dynamic conditions of generation and demand, allowing them to adapt to the specific real-world conditions of each region.

Contribution and Scope

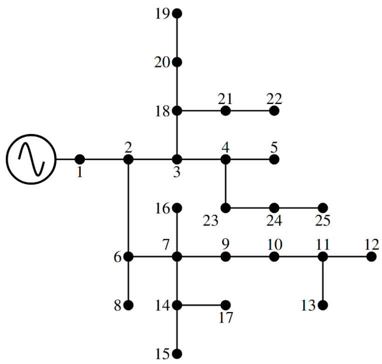
The literature review underscores the necessity for methodologies to integrate and operate distributed generation (DG) sources within unbalanced three-phase distribution systems. This need arises from the variations in energy generation and demand, along with associated operational constraints. This research introduces a leader-follower methodology aimed at optimizing this integration. It presents a mathematical model that combines a technical objective function with operational constraints, alongside an operational and statistical evaluation applied to a test system that is adapted to dynamic conditions in energy generation and demand.

Methodology

This work proposes a leader-follower methodology for the optimal integration of photovoltaic DG sources in unbalanced three-phase EDS. To this end, a mathematical model is presented with an objective function focused on reducing energy losses in a 25-node unbalanced three-phase test system, whose graphical representation is shown in Figure 1.

Figure 1

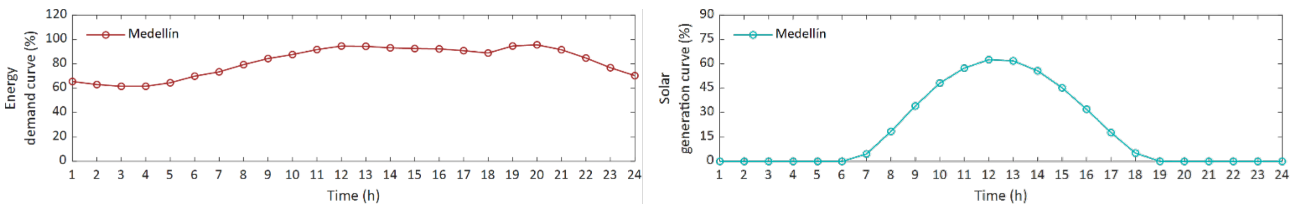
Graphical representation of the 25-node test system.



Additionally, the model considers a set of operational constraints, which include: the balance of active and reactive power at each node, the power limits for both conventional and distributed generators, voltage limits at the nodes, and current limits through the distribution system lines. All of this is evaluated in a test scenario adapted to real conditions of energy generation and demand, specifically during a typical operational day in the city of Medellín, Colombia (Guzmán-Henao et al., 2024). The behavior of energy demand and the generation potential associated with photovoltaic generators can be observed in Figure 3.

Figure 2

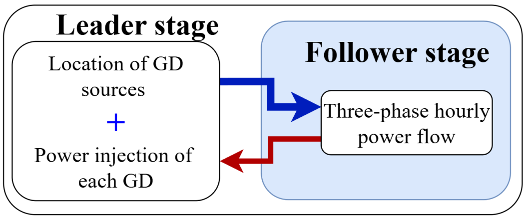
Energy demand and photovoltaic generation potential during a typical day in the analyzed region.



The leader-follower methodology consists of two stages. The first stage, referred to as the "leader" stage, employs a Particle Swarm Optimization (PSO) algorithm to suggest the location and amount of power injected by the DG sources (Eberhart & Kennedy, 1995). Meanwhile, the "follower" stage applies a three-phase load flow based on the Successive Approximations (SA) method (Montoya et al., 2020), which enables the representation of the system's unbalanced behavior. This three-phase SA method evaluates the impact of the integration and operation of DG sources, as suggested by the "leader" stage, on the operational conditions of the system. Furthermore, the SA method allows for quantifying the improvements achieved in the proposed objective function, which in this case is the reduction of energy losses in the EDS. Figure 3 illustrates the operational flow of the proposed methodology.

Figure 3

Operational flow of the leader-follower methodology.



Research Results

After establishing the baseline case, the proposed methodology was evaluated on 100 occasions to validate the reproducibility of the obtained solutions and the processing time required for each. It is important to mention that each of the 100 evaluations met the set of constraints associated with the proposed mathematical model. Table 1 presents a summary of the main results obtained following the evaluation of the methodology.

Table 1

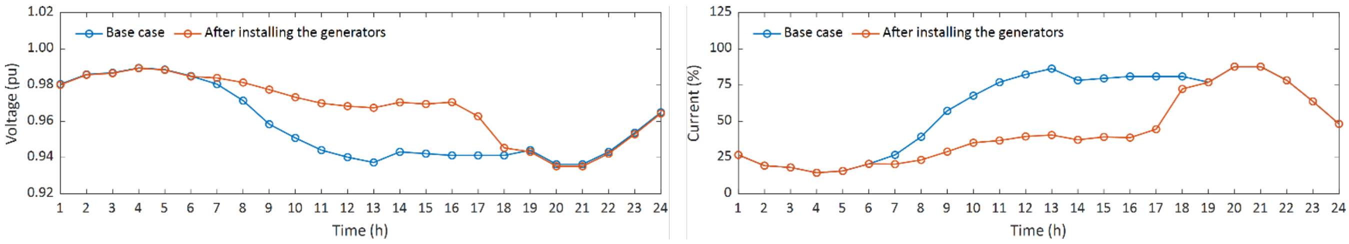
Summary of the results obtained from the 100 evaluations of the leader-follower methodology.

Methodology	Average time per solution (s)	Standard deviation (%)	Energy losses (kW)	Reduction Energy losses (%)
PSO-AS	78	0.0852	635.0805	34.5684
Base case	------	------	970.6026	------

In Table 1, the best solution obtained through the methodology is presented, achieving a reduction in energy losses of 34.5684% during a day of operation of the test system. It is also observed that the employed technique demonstrates adequate reproducibility and short processing times, which are critical factors for this type of methodology. Regarding the operational analysis, it is essential to emphasize that each proposed solution resulted in significant improvements in voltage profiles at each node and in the loading levels of distribution system lines during the power injection interval. Notably, phase A of node 11 exhibited the highest voltage, reaching a value of 0.9977 p.u., which complies with regional regulations stipulating that p.u. voltages for this type of distribution system must remain within +5% and -10% of the nominal voltage. Additionally, the performance of the line with the highest loading percentage following the installation of DG sources was validated, specifically line 8 in phase A. Figure 5 illustrates these variables both before and after the installation of DG sources.

Figure 4

Voltage in phase A of node 11 and loading percentage in phase A of line 8 before and after the installation of DG sources.



Conclusions

The proposed methodology proved to be an effective tool for optimizing the installation of DG sources. This study demonstrated a 34.57% reduction in energy losses compared to the baseline case. Furthermore, the combination of the PSO algorithm with the three-phase SA method yielded high-quality solutions, with adequate reproducibility and a percentage standard deviation of 0.0852, all achieved in reduced processing times. Additionally, it is noteworthy that the test scenario was evaluated under dynamic conditions of energy demand and generation, considering the three-phase nature of the system and the resulting imbalance from the different loads at each node's phases. Finally, as future work, it is anticipated that the simultaneous integration of other types of distributed energy resources, such as battery storage systems and reactive power compensation devices, will be explored.

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