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A Comprehensive Review of Distributed Generators Connection with Smart Distribution Networks: Optimization Strategies and Reconfiguration Synergy

Abdelazim.Salem[1*],Adel.Elsamahy[2], Rasha Elazab[2], M. Kassem[1]

[1]Department of Electrical Engineering, Faculty of Engineering, October 6University,6thof October City, 12585, Giza, Egypt.
[2] Department of Electrical Power and Machine, Helwan University, Egypt.

*Corresponding author email: abdelazim.salem.eng@o6u.edu.eg.
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Abstract- Distributed Generators (DGs) connected to modern power distribution systems offer significant benefits such as minimizing the power losses, and improving the voltage level on network buses,so the systems become more reliable. However, these benefits are heavily dependent on the best selection of placement and sizing of DG sources. This article provides a wide-rangingstudy of methodologies for DG placement and sizing, with a focus on both classical and intelligent optimization techniques including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), and hybrid approaches. Furthermore, the study highlights the role of power flow algorithms—both node-based and branch-based, accurately modeling DG behavior in distribution systems. Special emphasis is placed on thecoordinated integration of DGs with Distribution Network Reconfiguration (DNR), a critical smart grid function that enables dynamic topological adjustments to minimize power losses and restore service during contingencies. Through a structured comparison of literature, performance metrics, and algorithmic approaches, the paper identifies gaps and emerging trends that are essential for future research and real-world implementation in smart and sustainable power networks.

Keywords:Distributed Generation (DG); Optimal Placement; Power Flow Algorithms; Smart Grid; Distribution Network Reconfiguration (DNR); Metaheuristic Optimization.

1.Introduction

A fundamental understanding of the structure and operation of electric power systems is vital for analyzing and optimizing distribution networks. These systems comprise three primary subsystems generation, transmission, and distribution operating in a coordinated manner to deliver electrical energy efficiently and reliably across various voltage levels in response to consumer demand [1]. Electric power generation converts primary energy sources (e.g., coal, hydro, wind, solar) into electrical energy, typically at relatively low voltages. High-voltage transmission systems then transport this energy over long distances, with voltage levels elevated through step-up transformers to minimize losses. Near load centers, step-down transformers reduce voltages for safe distribution to end-users. The distribution network, operating at voltage levels ranging from 34 kV to 120 V, supplies electricity to residential, commercial, and small industrial customers. In recent years, the growing integration of Distributed Generation (DG) such as rooftop photovoltaics, wind turbines, and biomass systems into distribution systems has transformed the conventional operational paradigm. DG enhances grid resilience, supports decarbonization efforts, and offers localized power generation, reducing transmission losses and improving voltage profiles. Electrical powernetworks generally work with the following principles:

- Use of three-phase alternating current (AC) for efficient power transfer and equipment standardization.
- Hierarchical voltage transformation, enabling long-distance transmission followed by localized distribution.
- Interconnected subsystems that ensure redundancy, operational flexibility, and reliability.

The DN is radially connected system, especially in real-world utility operations, where nodes (buses) are connected by branches (lines) in a tree-like structure. Analyzing power flow within these radial networks involves solving nonlinear equations that account for voltage drops, power losses, and varying load conditions [2], [3]. Accurate modeling and optimization of these systems are critical, particularly with the increasing deployment of DG units and the advancement of smart grid functionalities.

2. Smart Grid Integration

Smart Grid (SG) introduces digital technologies and bidirectional communication to modernize conventional power systems, enabling improved efficiency, reliability, and flexibility in energy management. Key functionalities include real-time monitoring, automated fault detection, integration of distributed generation (DG), and demand-side response mechanisms [4].SG capabilities are particularly relevant to [insert specific relevance: e.g., the integration of DG units, power flow optimization, or enhanced network observability. The ability of SG systems to support decentralized energy sources, reduce operational costs, and enhance system resilience forms a vital component of modern power distribution strategies. These core functionalities include, see Figure 1:

- Automated fault detection, isolation, and reconfiguration.
- Real-time diagnostics of transformers and transmission lines.
- Integration of FACTS, smart switches, and energy storage.
- Adaptive protection and fault localization using sensor networks.
- Coordinated reactive power control and autonomous T&D operations.
- Consumer empowerment through advanced metering and real-time data access.

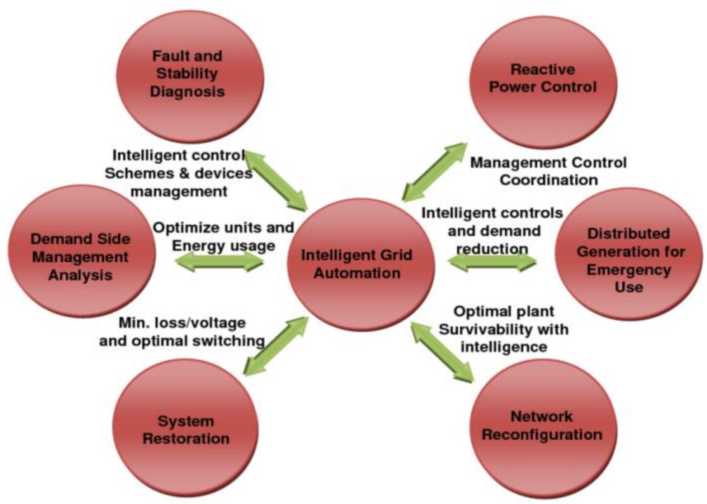

Figure 1: Functions of smart grid

3. Review of Distributed Generation (DG) Units

Distributed Generation (DG) refers to decentralized; small-scale electricity sources that are typically connected to the distribution network close to end users [5]. DG deployment has expanded significantly, fueled by market liberalization, energy diversification, and the increasing role of renewables in power systems. DG systems offer a wide range of benefits, including power loss reduction, voltage support, improved reliability, and deferred infrastructure investments. These advantages are particularly evident when DG units are sited strategically within distribution networks. However, renewable-based DG introduces variability due to its dependence on environmental conditions [6]. Technical analyses in recent literature address the integration of DG using network reconfiguration, capacitor placement, and DG optimization techniques. A simplified two-bus DG integration scenario is shown in Figure. 2 [7].

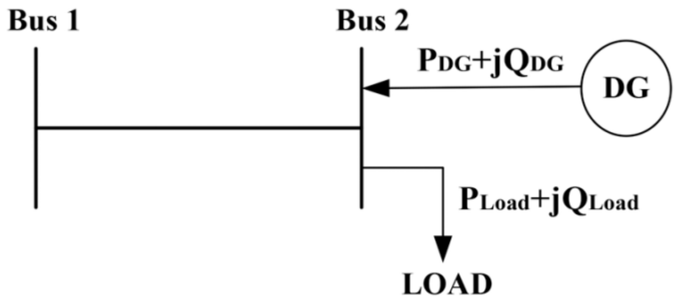

Figure 2: Simple DN with DG [16]

$$P_{line-loss} = R\left(\frac{(P_{load}-p_{DG})^2+Q_{load}-(\pm Q_{DG}))^2}{(V_2)^2}\right) \quad (1)$$

$$P_{line-loss} = R \times \left(\frac{(p_{load})^2+(Q_{load}-(\pm Q_C))^2}{(V_2)^2}\right) \quad (2)$$

These equations highlight the role of active and reactive power in influencing line losses. While DGs are often designed for unity power factor operation per IEEE 1547 [8], coordinated use of capacitors can mitigate losses. DG technologies range from combustion engines and fuel cells to renewables such as wind and solar [9], which now account for over 14% of global electricity supply [10]. DG systems offer quick deployment, lower emissions, and reduced reliance on long-distancetransmission, improving overall system resilience [5].

3.1. Types of Distributed Generation Systems

Distributed Generation (DG) systems include a broad mix of conventional and non-conventional technologies, ranging from combustion engines and micro-turbines to renewable energy sources and energy storage units. Conventional DGs, like reciprocating engines and gas turbines, are typically fossil-fuel-based and geographically dispersed. In contrast, non-conventional DGs such as PV systems, wind turbines, and fuel cells offer cleaner energy alternatives. Since many of these technologies generate DC power, inverters are essential for conversion to AC before grid integration. Wind turbines often use induction generators for direct grid connection, while variable-speed systems and micro-turbines typically employ power electronic converters for enhanced flexibility. DG systems are integrated into the grid using synchronous generators, induction machines, or static converters, with each approach selected based on source characteristics and network requirements. Power electronic interfaces, despite higher costs, enable better control, higher efficiency, and improved grid compliance.

4. Distributed Generation Units and Modeling for Conversion Devices

The modeling of Distributed Generation (DG) is vital for assessing its integration into electrical distribution systems. A common approach used when power flow study with fixedloadpower, where some DGs are modeled as PQ nodes. More advanced models treat DG units as synchronous or asynchronous machines connected via power converters, depending on the control strategy [11][12]. DGsare sorted into four main kinds with respect to the power transfer from them and their characteristics [13]:

1. **Type 1**: Provides only active power, such as photovoltaic systems connected via power converters.
2. **Type 2**: Synchronous machines, like cogeneration units,thatprovide both active and reactive power.
3. **Type 3**: Synchronous compensators, which provide reactive power alone.
4. **Type 4**: Induction generators and DFIGs, which deliver active power while absorbing reactive power.

Power electronics have high effects on DG operation, especially for renewable sources like solar and wind, which often require converters for efficient grid connection. The characteristics of DG output are influenced by the type of conversion unit, such as induction generators providing real power and absorbing reactive power, or static converters maintaining a constant power factor under normal conditions. DG models can be further sorted as fixed PF, fixed operated voltage, and changeable reactive outputs, enhancing the accuracy of power flow study in unsymmetrical loading network shaving high R/X ratios [14][15].

5. DG Modeling Approaches

Modeling the behavior of DGs in power systems is essential for accurate analysis. This paper considers three types of DG models based on their control strategies:

A. Constant Power Factor DG

Applicable to synchronous and inverter-based DGs, these sources work with fixed PF. The imaginary power is calculated as follows [16]:

$$Q_{iDG} = P_{iDG}\, tan(cos^{-1}(PF_{iDG})) \quad (3)$$

But the DG current is determined by Eq. 4.

$$I_{iDG} = I^{i}_{iDG}(V_{iDG}) + jI^{i}_{iDG}(V_{iDG}) \quad (4)$$

P_{iDG} and V_{iDG} are the real power and voltage at the DG output respectively; PF_{iDG}isith DG power factor, $Q_{iDG}$is the DGs imaginary power, and $I_{iDG}$is DG current.

B. Variable Reactive Power DG

This model suits induction generators whose reactive power changes with active power generation. A quadratic function is used [17]:

$$Q_{iDG} = -Q_0 - Q_1 P_{iDG} - Q_2 P^2_{iDG} (5)$$

Q_{iDG} is imaginary power needed to wind turbine while Q_0, $Q_1$and $Q_2$are obtained experimentally. In situations where the DN cannot deliver the imaginary power provided by the load, condensers connected for improving the system's PF [18]. In this case, the imaginary power of IG can be obtained from Eq. 6

$$Q^{i}_{i,g} = Q^{1}_{i,g} + Q^{c}_{i,g} \quad (6)$$

$Q^{c}_{i,g}$is imaginary power delivered from condensers.

C. Fixed Voltage DG

For voltage-regulated DGs, reactive power is adjusted iteratively to maintain constant voltage levels using a two-loop method [19]:

$$P^{k,m+1}_{i,g} + jQ^{k,m+1}_{i,g} = P^{k,m}_{i,g} + j(Q^{k,m}_{i,g} + \Delta Q^{k,m}_{i,g} \quad (7)$$

Where, $\Delta Q^{k,m}_{i,g}$is the required reactive power. This ensures the DG supports both real power injection and voltage control.

6. Power Flow Analysis with Integrated DGs

Power flow algorithms must be adapted to account for the presence of Distributed Generators (DGs). Two main solution techniques exist based on the modeling approach: **bus-algorithms** and **branch-algorithms** [19].

- **Bus algorithms** treat voltages or injection currents as variables and include techniques such as the bus impedance matrix, NR, and fast decoupled power flow [20-22].
- **Branch-algorithms** dealwith the currents or powers as states, relying heavily on impedance models and sweep/loop analysis [20].

DG sources may be treated as **PQ** or **PV** buses. PV-modeled DGs must adhere to reactive power limits; if these limits are exceeded, they are converted to PQ nodes. The power flow solution assumes:

- A **slack bus** with fixed voltage magnitude and angle,
- Initial node voltages equal to the slack bus,
- Zero power loss across branches for the first iteration.

These modifications are essential for accurate analysis under significant DG penetration.

Optimal DG Allocation in Distribution Systems

Distributed Generators (DGs) improve voltage profiles and reduce losses by supplying local power. However, their benefits depend critically on **optimal placement and sizing** [21]. Initial analytical techniques aimed to minimize losses by sequential DG placement, evaluated through load flow methods [22]. Though accurate, methods like the Newton-Raphson approach become impractical for large networks due to computational demands [23]. To overcome this, backward–forward sweep techniques were introduced, as in Nanghoguina's work, where DG sizes are computed using branch current injections and voltage magnitudes. AI-based methods have since gained traction:

- **GA** [24] and **PSO** [25] are widely used.
- A hybrid GA–PSO method was proposed in [26], though both face stagnation issues.
- Fitness functions often include loss minimization and voltage profile improvement using weakest-bus criteria [27].

Many studies assume DGs as PQ nodes with fixed output, limiting realism under variable loads.

Advanced approaches include:

- Hybrid PSO for load ability enhancement with different load models [5-28],
- Grey Wolf Optimizer under time-varying conditions [29],
- Combined PSO, GA, and GSA for urban substations [30],
- BB-BC algorithm for balanced/unbalanced systems [31],
- Multi-objective Honeybee Mating optimization for renewables [32], and
- Coordination of harmonics and protection constraints in DG placement [33].

Isolated DG placement using PV and biomass was studied by [35], with a focus on standalone systems.

6.1. Allocation Problem of Distributed Generators

In distribution networks, the integration of Distributed Generation (DG) provides local power supply to loads, reducing the distance between power generation and consumption. This results in a reduction in total power losses and an improvement in the system's voltage profile. The optimal positioning and spacing of DGs within the network are crucial for maximizing the potential benefits. To ensure the system operates efficiently, the optimal output of DGs must be carefully controlled to avoid any negative impacts on the distribution network [21]. To achieve the maximum benefits from DG, an analytical approach has been proposed to optimally allocate DG units with the objective of minimizing total power losses in the primary distribution network [22]. In this approach, DG units are sequentially placed in the network, and the corresponding power losses are evaluated. A conventional iterative search technique combined with Newton-Raphson (NR) load flow was considered in [23], but this method requires a significant amount of computation, making it unsuitable for large-scale networks. Nanghoguina introduced a method for determining the correct size and location of DG units using a backward–forward sweep technique, which calculates power losses based on the injected current in the branches. The DG size is then determined using the injected current and its equivalent voltage magnitude. Various optimization techniques have been applied to solve the DG location and sizing problem in distribution systems. For instance, Genetic Algorithm (GA) [24] and Particle Swarm Optimization (PSO) [25] are examples of artificial intelligence algorithms used for optimal DG placement and sizing. Ref. [26] proposed a combined discrete method that integrates GA and PSO to address this problem; however, both algorithms tend to converge to local optima or reach a stagnant state. Additionally, the minimization of power losses and maximization of voltage stability have been considered as fitness functions, based on the weakest voltage bus [27]. However, in many of these approaches, DGs are modeled only as PQ nodes, where the real and reactive power output of the DG is constant.

Ref. [5] introduced a hybrid optimization technique to maximize the system's load ability by optimally allocating multiple DG units, considering various load models using PSO [28]. In [29], several loading conditions were handled by dividing the day into three levels, and the placement and sizing of DG were optimized using a modified Grey Wolf Optimizer. Ref. [29] explored three intelligent algorithms—PSO, GA, and Gravitational Search Algorithm (GSA)—for the optimal placement of DG units at Qom's distribution substation. Conversely, in [31], balanced and unbalanced distribution systems were considered for optimal DG placement and sizing using the Big Bang Big Crunch Algorithm, although this study focused solely on total power loss minimization as a single objective. Ref. [32] presented a multi-objective framework for the optimal placement of three types of renewable energy resources fuel cells with combined heat and power, photovoltaic systems, and wind turbines using a modified Honeybee Mating Optimization Algorithm, but the output power of these renewable sources lacked forecasting capabilities. Furthermore, Ref. [33] addressed the coordination of harmonic and protection limits in the optimal placement and sizing of different DG types. Kumar and Banerjee [24] studied the use of PV modules and biomass gasifiers for loss reduction, though their work focused only on isolated DGs in the power system. Key features of the previous research are summarized in Table 1

Table 1: Summary of Key Features in Distributed Generator (DG) Allocation Studies

Feature Category	Key Aspects Covered	Purpose in Paper	References
Optimization Techniques	GA, PSO, GSA, Grey Wolf, Hybrid methods (GA+PSO, modified GWO, etc.)	Compare strengths and limitations of metaheuristic approaches	[24] [25], [26] [28], [29] [30], [32
Objective Functions	Power loss minimization, voltage profile improvement, system loadability, harmonic coordination	Justify performance metrics used for optimization and evaluation	[21], [27], [5], [31], [33]
Approach Type	Analytical, Heuristic, Metaheuristic, Hybrid	Categorize problem-solving strategies in the literature	[22], [23], [26], [5], [30]
Performance Metrics	Voltage deviation, total power loss, loadability index, harmonic impact, fault restoration time	Identify evaluation benchmarks used in comparative studies	[24], [25], [27], [34], [36]
Simulation Conditions	Balanced vs. unbalanced systems, static vs. dynamic loading, single vs. multiple DGs	Highlight assumptions and system conditions considered in case studies	[33], [34], [35]
Smart Grid Functions	Distribution Network Reconfiguration (DNR), switching coordination, automation, protection adaptation	Emphasize coordinated control and real-time adaptability	[34], [35]– [36], [37]–[38]
Load Models	Constant power (PQ), voltage-dependent ZIP, multi-period/day models	Address diversity and realism in demand representation	[27], [31], [32], [35]

7. Research Gaps

1. **Limited Integration of DG Allocation with DNR:** While DG allocation and DNR have been widely studied individually, only a few works have addressed their **co-optimization**, especially under dynamic operating conditions. More comprehensive frameworks are needed to simultaneously optimize DG placement and feeder reconfiguration.

2. **Inadequate Consideration of Protection Coordination:** The integration of DGs and DNR introduces challenges in protection device coordination due to bidirectional power flows. Many existing methods ignore **adaptive protection schemes** that adjust settings based on reconfiguration or DG output variability.

3. **Insufficient Modeling of Renewable DG Forecasting:** Several studies assume constant DG output, often modeling PV or wind sources as PQ nodes. However, **stochastic and forecast-based models** that consider intermittency and forecasting errors are necessary for realistic planning.

4. **Over-Reliance on Single-Objective Optimization:** Most optimization frameworks focus only on minimizing power losses or improving voltage profile. There is a need for **multi-objective approaches** that also incorporate economic, environmental, and reliability metrics.

5. **Neglect of Real-Time Implementation and Scalability:** Many proposed algorithms are computationally expensive and tested only on small test systems. Research should explore **real-time applicability and scalability** of optimization algorithms for large-scale or urban distribution networks.

6. **Lack of Standardized Benchmarks for Comparative Studies:** Comparisons between algorithms and methodologies are often inconsistent due to varying test systems, assumptions, and performance metrics. There is a need for **benchmark datasets and standardized evaluation frameworks**.

8. Conclusion

This paper has provided an in-depth review of distributed generator (DG) allocation strategies, focusing on power flow modeling, optimization techniques, and their coordinated integration with smart grid functions like Distribution Network Reconfiguration (DNR). The review highlights a clear evolution from classical load flow and optimization methods toward intelligent and hybrid algorithms capable of handling modern distribution system complexities. However, several challenges remain, including the need for co-optimization of DG and DNR, protection coordination under dynamic reconfiguration, accurate modeling of renewable intermittency, and real-time implement ability. Future research should prioritize the development of scalable, multi-objective, and adaptive optimization frameworks that align with the goals of resilience, sustainability, and cost-effectiveness in smart grid environments. This direction will ensure the optimal utilization of distributed resources while maintaining the reliability and efficiency of distribution networks.

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