Distributed Generation: Benefits, Challenges and Impact on Electrical Distribution System and Protection

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Abstract: *With the rapid advancement of technology and growing concerns about environmental impacts, small-scale generation sources, known as Distributed Generation (DG), are increasingly integrated into distribution networks. However, for these systems to operate efficiently and reliably, their design must account for computational feasibility. DG systems often rely on electronic power converters, which can interfere with protective device coordination, lead to feeder mis-tripping, increase fault levels, and cause overvoltage issues within the power grid. Therefore, it is crucial to thoroughly assess the benefits, challenges, and impacts of DG on existing distribution and protection systems. This research paper focuses on reviewing these aspects through comprehensive study of integration of DG in power system*

Keywords: *Environmental Impacts, Distributed Generation, Distribution Networks, Protective Device, Generation Sources, Reliability.*

I. Introduction

Distributed Generation (DG) refers to electricity-generating units that connect directly to the distribution network rather than the transmission grid. DG plays a crucial role in the expanding deployment of Distributed Energy Resources (DERs) across distribution systems [1-3]. These units can vary in size, ranging from large-scale plants to smaller localized energy sources. The adoption of DG has grown significantly in deregulated power markets due to its ability to address localized energy demands and alleviate transmission bottlenecks from centralized power plants [4, 5].

DG resources encompass a diverse range of energy technologies, including turbines, photovoltaic (PV) systems, fuel cells and energy storage devices, with capacities typically ranging from 1 kW to 10 MW [2]. Integrating DG into distribution networks transforms their operation from passive to active systems. This shift can enhance network reliability, minimize line losses, improve voltage stability, lower pollutant emissions, boost overall energy efficiency, and reduce power delivery costs by placing generation closer to demand centers [6-9].

Despite these benefits, DG integration also introduces challenges, such as increased fault currents and reduced sensitivity, selectivity, and real-time control in distribution network protection [3]. As utilities transition to performance-based rates and market restructuring, addressing these challenges becomes essential to fully harness the advantages of DG. Effective planning is necessary to mitigate negative impacts and optimize DG placement and capacity for enhanced distribution network performance [7, 10-12].

DG can generally be categorized into two types: inverter-based DG and rotating machine DG. Inverter-based systems use inverters to convert generated power—whether AC or DC—into a grid-compatible form, facilitating smooth and cost-effective integration with the utility grid. DG relies on mechanical equipment, such as motors or synchronous generators, to convert and transmit electrical power. These systems are well-suited for islanding applications due to their robust and responsive governor systems [4, 13-15].

Table 1 highlights various DG technologies and their generation levels. For this research, the focus is on micro-scale DG utilizing photovoltaic (PV) solar technology. PV solar power operates as a DG source by injecting real power into the distribution network [16, 17].

Table 1: Different distributed generation levels and technology

S/No.	Type	Size	DR Technologies
1	Micro DG	1 W < 5 kW	Solar Technology
2	Small DG	5 kW < 5 MW	Fuel Cell, Wind Turbine, Biomass among others
3	Medium DG	5 MW < 50 MW	Geothermal
4	Large DG	50 MW < ~300 MW	Hydrogen Energy System

A. Benefits of DG on distribution system

Integrating Distributed Generation (DG) into distribution networks provides several significant advantages, which can be categorized as follows: [6, 9, 18, 19]

i. **Technical Benefits:** Depending on factors such as location, capacity, and technology, DG can deliver a range of technical improvements. These include reduced line losses, enhanced voltage stability, improved power quality, and greater system reliability and security.
ii. **Economic Benefits:** DG can lead to cost savings and financial gains through deferred infrastructure upgrades, lower operational and maintenance expenses for certain technologies, and increased productivity. Additional economic advantages include reduced healthcare costs driven by environmental improvements, lower fuel expenses from enhanced efficiency, decreased reserve requirements and minimized operating costs through peak load reduction.
iii. **Environmental Benefits:** DG technologies contribute to a cleaner energy landscape by lowering pollutant emissions and promoting the use of renewable energy sources, thereby supporting sustainable power generation.

B. Challenges and effects of DG on distribution system

Despite the environmental and economic benefits that Distributed Generations (DGs) bring to power systems, they also introduce certain drawbacks. DGs are typically defined as electric power sources that are directly connected to the distribution network or positioned on the consumer side of the meter [10]. When DG units generate power, it can be injected at various points along the feeder, potentially altering the conventional flow of electricity. This shift becomes more pronounced as the penetration level of DGs increases [20-24].

Some notable drawbacks of DG integration include the introduction of voltage harmonics, challenges with dynamic stability, and issues related to protection coordination. However, the most significant concern is the impact of DGs on the protection systems. The integration of DGs modifies the structure and electrical characteristics of distribution networks [11, 19]. Traditionally, distribution networks follow a radial design, and their protection systems are structured accordingly. The addition of DGs disrupts this by introducing bidirectional current flow and creating looped configurations [25-30].

Furthermore, the inclusion of DGs can alter fault current levels, potentially disrupting protection coordination. Existing protection schemes, which are designed for conventional systems, may not provide adequate coverage in DG-integrated networks. High DG penetration can lead to scenarios where distribution networks operate both in connection with and isolation from the main grid [6, 21, 25]. This necessitates the development of new network planning strategies that account for evolving load configurations, ensuring technical constraints are met and DG benefits are optimized. Addressing these challenges is crucial before DGs can be fully integrated as viable alternative power sources [31, 32].

C. Effects of DG on distribution system protection

Power systems often encounter faults and experience power quality issues, underscoring the importance of effective system protection. Power system protection involves identifying faults or irregularities within system components and isolating affected areas to prevent further damage [2, 8]. Protection mechanisms in distribution networks typically include feeder breakers controlled by relays, reclosers positioned within and beyond substations, line sectionalizers, and fuses. These measures are essential to safeguard the public, enhance system stability, prevent equipment damage, and mitigate overload condition [14, 17, 28]s.

Over current protection devices, such as fuses, relays and circuit breakers, play a crucial role in system protection. These devices monitor current flow and when anomalies are detected, interrupt the circuit to isolate the affected section [29, 31, 32].

However, integrating Distributed Generation (DG) into distribution systems can elevate fault levels near the connection point. This increased fault level may push the distribution system closer to its fault tolerance limit [12]. In such cases, equipment damage, operational failures, personnel safety risks and supply disruptions may occur. DG integration may also introduce coordination challenges, potentially causing larger sections of the network to be isolated. Proper protection at the DG connection point is crucial to prevent damage to both DG and utility infrastructure, ensuring seamless parallel operation with the grid [5, 16, 24].

Interconnection protection serves to shield the grid from potential disturbances caused by DG units during parallel operation [14]. This protective system can be installed on either the primary or secondary side of the interconnection transformer, depending on the system design. The design of interconnection protection systems depends on factors such as generator size and type, point of interconnection and transformer configuration [19, 27, 29, 31].

Utilities typically define interconnection protection requirements, which include:

i. Disconnecting the generator upon detection of islanding conditions, where DG units cease parallel operation with the grid.
ii. Protecting the grid from DG-induced damage, such as fault currents and transient over-voltages.
iii. Safeguarding DG units from grid-related issues, including automatic reclosing events.

II. Distribution Load Flow with DG Incorporation

Incorporation of DG model into the distribution lines was done to improve power system performance, enhance power flow control and voltage control, and decrease capital investment. This is done mathematically by modelling the distribution load flow with inclusion of DG as shown in Figure 1 [7]. With DG integration into the network, mathematical modeling of FBS load flow with DG based on power loss was done [13].

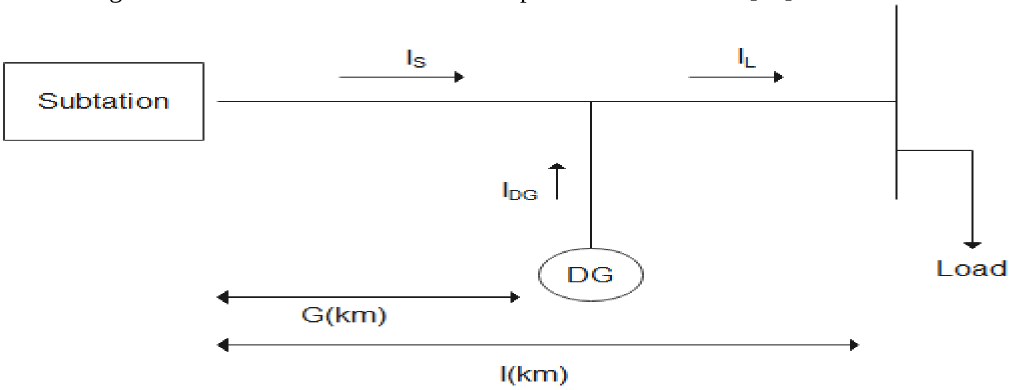

Figure 1: Distribution network with incorporation of DG

The amount of power loss in the absence of DR can be calculated as shown in Equations (1) to (2):

$$I_S = I_L \tag{1}$$

$$P_{Loss}^{Without,DR} = 3R_L \times (I_L)^2 \tag{2}$$

The amount of power loss in the presence of DG can be calculated as shown in Equation (3)

$$P_{Loss}^{With,DR} = P_{Loss1} + P_{Loss2} \tag{3}$$

Thus equation (4) can be expressed as shown in Equation (4):

$$P_{Loss}^{With,DR} = 3R_G \times (I_S)^2 + 3(I - G)R \times (I_L)^2 \tag{4}$$

The variation of power loss after installing DG is obtained as shown in Equation (5):

$$\Delta P_{Loss} = 3R_G \times (I_S)^2 + 3R_G \times (I_L)^2 \tag{5}$$

The current in the network is given as shown in Equation (6):

$$I = \left(\frac{S}{3 \cdot V}\right)^* \tag{6}$$

After installing DG, the following Equation (7) stands:

$$|I_S| = |I_L - I_{DR}| \tag{7}$$

Substituting equations (7) and (6) into equation (5), this gives equation (8):

$$\Delta P_{Loss} = \frac{R_G \left(\left(S_L^* \cdot V_{DR}^* - S_{DR} \cdot V_L^* \right)^2 - \left(S_L^* \cdot V_{DR}^* \right)^2 \right)}{3\left(|V_L^*| \cdot |V_{DR}^*| \right)^2} \tag{8}$$

It can be concluded from equation (8) that identifying an appropriate size for a DG unit plays significant role in reducing the power loss. On the other hand, if the considered size is inappropriate, it may increase the power loss.
where; $P_{Loss}^{Without,DR}$ is the power loss in the network in the absence of DG, R_L is the resistance of the line per length, I_L is the current of customer terminal, $P_{Loss}^{With,DR}$ is the power loss in the presence of DR, P_{Loss1} is the power loss from the substation to DR location, P_{Loss2} is the power loss from DR location to load location, G and I are distance between substation to DR and to load respectively.

III. Optimal Power Flow for DG Placement

Optimal Power Flow (OPF) plays a crucial role in the planning and operational phases of power system management [3, 9]. It is designed to optimize a specific objective while adhering to network power flow equations and the operational limits of system components. By adjusting control variables, OPF seeks to achieve conditions that either minimize costs or maximize efficiency under defined operating scenarios. Common control mechanisms include modifying active and reactive power outputs, switching shunt capacitors or reactors, adjusting transformer taps, and redistributing loads [14, 18, 26].

The economic principles guiding OPF are shaped by various mathematically derived parameters, known as constraints. These constraints are typically classified as either equality or inequality conditions. Equality constraints represent power flow equations, while inequality constraints encompass operational limits such as branch flow capacities and permissible voltage levels at buses. By translating these constraints into equations, the load flow problem can be defined, and the solution to these equations yields the optimal power flow configuration [13, 17]

Mathematically, the general OPF problem can be expressed as shown in Equations (9) to (11) [6].

$$Miniize \;\; f(x,u) \tag{9}$$

Subject to:

$$g(x,u) = 0$$
$$h(x,u) \le 0$$
$$u^{Min} \le u \le u^{Max} \tag{10}$$
$$x^T = \left[P_G, V_L, \ldots V_{L_{NL}}, Q_G, \ldots Q_{G_{NG}}, S_l \ldots . S_{l_{nl}}\right] \tag{11}$$
$$u^T = \left[V_G \ldots . V_{G_{NG}}, P_G \ldots . P_{G_{NG}}, T_l \ldots . T_{NT}, Q_C \ldots . Q_{C_{NC}}\right] \tag{12}$$

where; f is the objective function to be minimized, g is the power flow equations equality constraints, h is the system operating constraints , x is the vector of the system dependent variables, u is the vector of control variables, u^{Min} and u^{Max} is the minimum and maximum feasible region of control variables, V_L is the load bus voltages, P_G is the slack bus active power outputs, Q_G is the generator reactive power outputs, Q_C is the shunt VAR compensator, S_l is the transmission line loadings, T_l is the transformer tap settings, NL is the number of load buses, NG is the number of generators, NT is the number of regulating transformers, NC is the number of shunt compensators, nl is the number of transmission line.

Several methodologies for solving optimal power flow have been proposed and implemented on different test systems [22]. The OPF methods are broadly grouped as conventional and intelligent method as shown in Table 2. Conventional methods are based on mathematical programming approaches and used to solve different size of OPF problems. These methods are weak in handling qualitative constraints, have poor convergence and may get stuck at local optimum. Examples are Gradient Method (GM), Dynamic Programming (DP), Linear Programming (LP), Quadratic Programming (QP), Newton Methods (NM), Lagrangian Relaxation Algorithm (LRA), Non-Linear Programming (NLP) and Interior Point (IP) methods. Many of these conventional techniques are employed most especially when the search space is non-linea [23, 25, 28]r.

Table 2: OPF solution methodologies

OPF Methods	
Conventional Method	Intelligent Method
Gradient Method	Genetic Algorithm
Newton Method	Particle Swarm Optimization (PSO)
Linear Programming Method (LP)	Ant Colony Optimization
Quadratic Programming (QP) Method	Artificial Neural Network
Interior Point Method	Salp Swarm Algorithm

Intelligent methods also referred to as heuristic or meta-heuristic optimization techniques, are employed to address the limitations of traditional methods [11]. These approaches are highly adaptable, particularly when dealing with diverse qualitative constraints. They have the ability to identify multiple optimal solutions within a single simulation run. Some examples of such methods include Cuckoo Search Algorithm (CSA), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Firefly Algorithm (FA), Differential Evolution (DE), Artificial Bee Colony (ABC), Salp Swarm Algorithm (SSA), and Whale Optimization Algorithm (WOA) [24, 28, 32]

To determine the optimal location and correct size of DG units in a distribution system, thereby minimizing power losses, fault currents, protection relay mis-coordination, and enhancing the voltage profile, it is essential to apply a meta-heuristic optimization algorithm. These techniques are robust, providing near-optimal solutions for large and complex DG placement problems, offering significant advantages over conventional methods.

IV. Related Works on DG Integration into Power System

Significant efforts have been directed at examining and addressing the challenges of integration of DG into electrical power. Table 3 provides a summary of the reviewed studies, highlighting their methods and limitations in the context of the impact and benefit of DG

Table 3: Summary of various research and their limitations

Author	Topic	Algorithm Used	Limitation
Abbasi *et al*. (2013) [1]	Adaptive protection coordination scheme for distribution network with DG	Over current and under-voltage protection	The approach cannot be guaranteed for optimal solution of power system protection.
Rahman and Das (2014) [28]	Impact of DG on power system protection	Reliability Index	the study did not consider power loss reduction after the DG placement.
Sheng *et al*. (2015) [32]	Adaptive current protection scheme for distributed systems with distributed generation	Digital relays	Reliability and time delay of the communication media were not investigated to make the protection system more robust and selective.
Cuilian *et al*. (2016) [19]	Protection scheme of distribution network with PV power supply.	Balanced PV capacity	The approach can cause some issues for networks, including repetitive synchronization of DG with the network.
Author	Topic	Algorithm Used	Limitation
Ibrahim *et al.* (2016) [17]	Adaptive protection coordination scheme for distribution network with distributed generation	Artificial Bee Colony (ABC)	The approach is complex and time-consuming process,
Shahzad *et al.* (2017) [31]	Protection of distributed generation: challenges and solutions	Review approach	The study was only based on reviews, no practical work was implemented.
Osabohien and Uhunmwangho (2018) [24]	Assessing the impacts of distributed generation on the protection scheme of a distribution network	Fault current limiter	The approach does not cover every possible mode, thus, could not be guaranteed for optimal solution for power system protection
Elhaffar *et al.* (2018) [13]	Management of distribution system protection with high penetration of DGs.	Adaptive protection	The proposed solution could not be guaranteed for optimal solution for power system protection
Jhansi (2019)	Effects of distributed generation on electrical power network and protection	Review of protection strategies	The study was only based on review no practical work was done.
Rahmani *et al.* (2020) [29]	An adaptive protection scheme for distribution networks with DG sources in various operational modes.	Existing setting groups in over current relays	The proposed solution could not be guaranteed for optimal solution for power system protection.
Ajenikoko *et al*. (2021) [5]	Analysis of the effect of distributed generation on loss reduction in electrical distribution network	Reviewed different approaches	The study only based on assumptions, no practical work was implemented.
Author	Topic	Algorithm Used	Limitation
Li *et al*. (2022) [21]	Mixed-integer linear programming models and algorithms for generation	Big-M formulation, hull formulation,	The result cannot be guaranteed for optimal solution for power system protection.

	expansion planning of power systems		
Sarjiya *et al.* (2023) [30]	Generation expansion planning with a renewable energy target and interconnection option	Open-source power expansion planning model	The approach could not be guaranteed for optimal solution for power system protection
Ajenikoko *et al.* (2024) [2]	Investigation of power loss reduction in electrical distribution network with incorporation of distributed generators	Ladder load flow algorithm	Different components of the DG and the economic value of the DG system to twere not presented.

V. Results of the Reviews

This research provides an in-depth review of various methods for enhancing protection systems in distribution networks, especially with the integration of Distributed Generation (DG). While many existing studies focus on adaptive overcurrent protection, challenges arise in certain scenarios where the minimum relay is reduced to less than 20% of the line length due to the presence of DGs, making adaptive current protection ineffective. Moreover, several of the existing techniques experience malfunctions caused by blinding issues, leading to failures in coordination with DGs. Consequently, there is a clear need for a reliable method that ensures an optimal and accurate solution for power system protection.

VI. Conclusion

This research paper reviews the benefits challenges and impacts of integrating Distributed Generation (DG) into electrical distribution and protection systems. DG offers advantages such as improved system reliability, reduced line losses, enhanced voltage stability and environmental sustainability through renewable energy. However, it poses challenges in adapting existing protection mechanisms to handle bidirectional current flow and varying fault levels, which can disrupt protective device coordination. To address this, advanced protection strategies tailored to DG's unique characteristics are needed. Successful DG integration also requires strategic planning for optimal placement and sizing within the distribution network, using optimization techniques like Optimal Power Flow (OPF). While progress has been made in protection schemes, further research is essential to manage the complexities of high DG penetration, ensuring safe and efficient integration that maximizes grid performance and reduces environmental impact.

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