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Review Article

Optimizing the integration of type C distributed generation systems for enhanced performance of medium voltage distribution networks: A review

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Abstract

The rapid evolution of electrical energy systems is increasingly driven by the integration of Distributed Generation (DG) technologies, particularly Type C systems such as solar photovoltaic (PV) installations. As the demand for sustainable, efficient, and reliable electricity continues to grow globally, these non-dispatchable renewable sources are emerging as pivotal in transforming medium voltage (MV) distribution networks. This review synthesizes recent advances in the optimal placement and integration of Type C DG units within MV grids, typically operating between 11 kV and 33 kV, with a focus on minimizing active power losses and enhancing voltage stability, two critical parameters in modern power systems. It examines the technical architecture of MV networks, explores DG classification and operational characteristics, and highlights the benefits and constraints of deploying PV-based DG. Emphasis is placed on optimization methodologies, implementation challenges, and enabling technologies such as smart inverters and energy storage systems. The findings underscore that, despite their intermittency, Type C DG units, when strategically integrated can significantly improve grid resilience, flexibility, and sustainability, supporting the evolution toward intelligent, decentralized, and future-ready smart grids.

1.0 Introduction

The rising global demand for reliable, efficient, and sustainable electrical energy has intensified efforts to modernize power distribution networks [1]. Among the various strategies employed, the integration of Distributed Generation (DG) units, particularly Type C DG such as solar photovoltaic systems, has emerged as a promising solution [2,3]. These non-dispatchable renewable sources, when optimally placed and sized, can significantly enhance power system performance by minimizing active power losses and improving voltage stability, both of which are vital concerns in the planning and operation of medium voltage (MV) distribution systems [4,5]. Electricity plays an indispensable role in modern society, powering domestic, industrial, commercial, and infrastructural activities. Any interruption in electrical supply can trigger far-reaching consequences, including the shutdown of factories, disruption of communication systems, and impairment of critical infrastructure. Thus, ensuring a consistent and adequate electricity supply is a top priority for national utilities and policymakers. The electric power system is structured into three primary components: generation, transmission, and distribution [6]. Generation systems, or power plants, convert energy typically thermal, into electrical energy, which is then transferred over long distances by transmission systems to the distribution network. The distribution system ensures that the generated electricity reaches end users efficiently and reliably [7]. Among the three types of distribution configurations, radial, loop, and mesh, the radial distribution system remains the most widely adopted due to its simplicity, cost-effectiveness, and ease of implementation. In a radial setup, power flows in a single direction from the substation to consumers along designated feeders. However, this architecture is susceptible to complete service interruptions if a fault occurs along the feeder path. Moreover, each feeder serves a distinct load profile depending on the number and type of consumers it supports, which influences voltage levels and contributes to power losses within the network [8].

As distribution systems expand and become increasingly complex, they face mounting challenges, particularly in terms of voltage regulation and power loss [9]. It is estimated that 10–13% of generated power is lost at the distribution level due to resistance, poor voltage profiles, and inefficient network configurations. These losses elevate operational costs and compromise system stability, making the need for technical interventions more pressing [10]. Addressing these challenges necessitates the deployment of intelligent solutions aimed at enhancing voltage stability and reducing active power loss. Optimal integration of Type C DG units into the MV distribution network represents a viable and cost-effective strategy to achieve these objectives. Their integration can significantly bolster grid resilience, improve voltage profiles along feeders, and reduce the strain on centralized power plants. This review provides a comprehensive analysis of recent developments in the optimal placement of Type C DG within MV distribution networks [11]. It synthesizes current research trends, advanced optimization techniques, and practical deployment considerations. Particular attention is given to the impact of DG placement on network performance, the application of modern algorithms for placement optimization, and the technical and operational constraints influencing real-world implementation. The overarching goal is to present an informed perspective on how strategically integrated DG can transform conventional distribution systems into efficient, stable, and future-ready smart grids [12].

This article is organized to include a comprehensive literature review that lays the theoretical foundation and provides the contextual background for the study. This is followed by a detailed presentation and analysis of the research findings, offering valuable insights into the collected data and their implications. The article concludes with a synthesis of the main findings, supported by well-reasoned conclusions and practical recommendations aimed at addressing the research objectives and guiding future work.

2.0 Literature Review

Medium Voltage distribution networks form a vital link between the high-voltage transmission system and the low-voltage networks that serve end users [13,14]. They typically operate within the voltage range of 11 kV to 33 kV and are responsible for delivering electricity to both urban and rural consumers with acceptable voltage quality, minimal losses, and high reliability [15,16]. These networks are embedded within the broader structure of electric power systems, which consist of three primary components: generation, transmission, and distribution. In this structure, electrical energy is first generated usually in large-scale centralized plants by converting thermal, hydro, nuclear, or renewable energy sources into electricity. This energy is then transmitted over long distances through high-voltage transmission lines before being stepped down in substations and distributed via MV networks [17]. Key components of MV distribution systems include primary substations, distribution feeders, transformers, protection equipment, and control systems. These elements work in tandem to ensure that electricity is delivered safely, efficiently, and reliably to end users.

MV distribution networks can be configured in one of three primary topologies: radial, loop, or mesh. Among these, the radial configuration is the most prevalent, particularly in developing countries, due to its simplicity, cost-effectiveness, and ease of maintenance [18]. In a radial system, power flows in a single direction from the substation to consumers along discrete feeders. While this layout simplifies design and fault detection, it also makes the system vulnerable to total feeder outages if a fault occurs. Loop systems, on the other hand, offer improved reliability by connecting feeders in a closed-loop structure [19,20]. Under normal operations, power still flows in one direction, but in the event of a fault, the loop can be reconfigured to maintain supply. Though more resilient than radial systems, loop configurations involve higher costs and more complex protection schemes. The mesh distribution system, typically used in high-demand urban areas, provides multiple paths for power flow [20]. This configuration offers the highest reliability and redundancy but demands advanced control, sophisticated protection mechanisms, and greater investment.

Despite their essential role, MV distribution networks face numerous technical and operational challenges. A major issue is the high level of active power losses incurred, primarily due to resistance in conductors and suboptimal feeder configurations [21]. These losses, which can amount to 10–13% of generated power, reduce efficiency and increase the cost of electricity. Additionally, voltage instability is a significant concern, especially in systems with long feeders or variable load profiles. Inadequate voltage regulation can impair equipment performance and lower service quality. Another pressing issue is the lack of flexibility in conventional radial networks, which hampers load redistribution and fault management [22]. Furthermore, traditional MV networks were not originally designed to accommodate DG, particularly variable renewable sources like solar PV. The integration of such sources poses challenges related to bi-directional power flow, protection coordination, and voltage fluctuation [23]. Compounding these issues is the ageing infrastructure in many regions, which struggles to cope with modern load demands and the dynamic nature of renewable energy. Environmental and geographical constraints, particularly in remote areas, also hinder system expansion and maintenance. Addressing these challenges is crucial to modernizing MV distribution systems and enabling the integration of intelligent, decentralized solutions such as optimally placed Type C DG units.

The reviewed literature [18-23] highlights that MV distribution networks are primarily configured in radial, loop, or mesh topologies, with the radial structure being most prevalent in developing countries due to its simplicity and low cost. However, radial systems are prone to complete feeder outages and lack the flexibility needed for effective fault management. Loop and mesh configurations provide improved reliability and redundancy but come with increased complexity and investment requirements. Across all network types, key challenges persist, including significant active power losses, voltage instability, and limited adaptability to modern energy demands. These issues are exacerbated by ageing infrastructure and the growing integration of distributed generation (DG), particularly variable renewable sources like solar PV, which introduce new technical difficulties such as bi-directional power flow and protection coordination. In conclusion, addressing these challenges is critical to improving the performance and resilience of MV distribution systems. The integration of intelligent, decentralized solutions such as optimally placed Type C DG units offers a promising pathway to enhance network flexibility, support renewable energy adoption, and ensure reliable power delivery in both urban and remote areas.

2.1. Distributed Generation in Distribution Networks

DG refers to the decentralized, small-scale production of electricity from power generation units located close to the point of consumption [24]. Unlike traditional centralized power plants, which rely on extensive transmission networks to deliver electricity over long distances, DG systems reduce transmission losses and enhance energy efficiency by supplying power locally. These systems may operate in conjunction with the main grid (grid-connected mode) or independently (islanded mode), depending on the network configuration and control strategy [25]. The growing adoption of DG has been driven by advancements in renewable energy technologies such as solar photovoltaics, wind turbines, biomass, and small hydropower, as well as the increasing implementation of smart grid infrastructure. DG plays a vital role in improving energy access, reliability, sustainability, and resilience, particularly in remote and underserved areas. Typical DG systems range in capacity from a few kilowatts to several megawatts and are designed to meet localized energy demands efficiently, as illustrated in Figure 1.

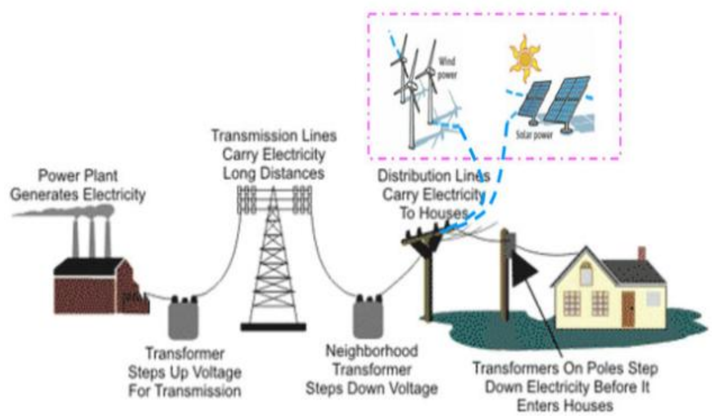

Figure 1: Typical Distributed Generation in Distribution Networks [26]

Despite its growing prominence, the definition of DG varies across the literature due to differing perspectives on its scale, location, and operational characteristics. The Authors in [27] broadly define DG as any electric power generation source that is connected directly to the distribution network or on the customer side of the meter, without imposing size limitations. The IEEE defines DG as "the generation of electricity by facilities that are sufficiently smaller than central generating plants to allow interconnection at nearly any point in a power system," emphasizing the flexibility in siting and integration (Photovoltaics & Storage) [28]. Organizations such as CIGRE and CIRED provide more detailed definitions based on technical parameters [29]. CIGRE, for example, describes DG as generation units with capacities ranging from 50 MW to 100 MW that are typically connected to the distribution network and are not centrally planned or dispatched [29]. Similarly, CIRED aligns with this capacity range, focusing on distribution-level integration.

The researcher in [30] describe DG as relatively small generation units of 30 MW or less that are situated near customer sites to address specific energy needs or enhance the economic operation of the distribution grid. The scholars in [31,32] expand the concept to include storage technologies, defining DG as small sources of electric power generation or storage, typically ranging from below 1 kW to tens of megawatts, located close to the load and outside the scope of large central power systems. In summary, while definitions differ, the core attributes of DG systems remain consistent: they are smaller in scale than conventional power plants, located near the point of use, and designed to either supplement or operate independently of the central grid [33,34]. These characteristics make DG a critical component of modern, flexible, and sustainable energy systems.

2.1.1 Types of Distributed Generation

Distributed Generation (DG) systems are commonly classified according to factors such as their primary energy source, operational characteristics, and the way they interact with the central power grid. A widely recognized classification groups these systems into four main types known as A, B, C, and D, each representing different levels of technological advancement, functional roles within the power system, and associated regulatory requirements. [35]. Type A DG systems consist of conventional fossil-fuel-based generators, such as diesel engines, gas turbines, and microturbines. These units are typically dispatchable, meaning they can be controlled to produce power on demand. Their ability to provide firm and reliable electricity makes them suitable for backup power applications, peak load management, and deployment in areas with unreliable or weak grid infrastructure [36]. However, their dependence on fossil fuels poses environmental challenges, making them less compatible with sustainable energy goals. Type B DG includes renewable-based but dispatchable or hybrid systems. This category features technologies such as biomass and biogas power plants, as well as hybrid setups like solar-diesel or wind-battery systems [37]. These solutions blend the benefits of renewable energy with the reliability of conventional sources or storage technologies, offering improved controllability. They are particularly useful in off-grid or remote locations where continuous power is necessary but renewable resources are inconsistent. Type C DG comprises non-dispatchable renewable energy systems, predominantly solar photovoltaic installations and small-scale wind turbines [38,39]. These technologies are environmentally sustainable and increasingly cost-competitive, yet their intermittent nature driven by variable weather conditions presents challenges for grid integration. Issues such as voltage fluctuations, reverse power flow, and the need for grid-supportive technologies like smart inverters or battery storage must be addressed to maintain stability and power quality within medium MV networks. Type D DG encompasses advanced and emerging technologies that promise high efficiency and seamless integration with smart grids [40].

Table 1: Classification of Distributed Generation (DG) Systems

DG Type	Primary Source	Dispatchability	Integration	Applications	Advantages	Challenges
A	Fossil fuels (e.g., diesel engines, gas turbines, microturbines)	Dispatchable	Grid-connected or standalone	Backup power, peak load shaving, weak-grid areas	Reliable, firm power supply	High emissions, fossil fuel dependence
B	Renewable-based dispatchable or hybrid systems (e.g., biomass, biogas, solar-diesel, wind-battery)	Partially Dispatchable	Grid-connected or standalone	Off-grid systems, remote locations	Blend of renewables and reliability, improved control	Resource variability, moderate complexity
C	Non-dispatchable renewables (e.g., solar PV, small wind turbines)	Non-dispatchable	Primarily grid-connected	Sustainable energy supply, urban/sub urban use	Low emissions, cost-effective, scalable	Intermittency, voltage fluctuation, grid integration.
D	Advanced/emerging technologies (e.g., fuel cells, CHP, hydrogen systems)	Highly flexible & efficient	Smart grid-compatible	Future smart energy systems, industrial use	High efficiency, cogeneration, low emissions	High cost, early-stage adoption, and technical maturity needed

Table 1 is a well-structured comparative table that differentiates Type A, B, C, and D Distributed Generation systems based on key attributes [39,40]. Key examples include fuel cells, Combined Heat and Power (CHP) systems, and hydrogen-based energy solutions. These systems often deliver both electricity and heat, thereby maximizing energy utilization. While their adoption is currently limited by cost and technological maturity, they represent a promising path toward flexible, clean, and intelligent energy systems. Each DG type introduces unique operational characteristics, control requirements, and compatibility considerations when deployed within MV networks. Their effective deployment calls for strategic planning, grid adaptability, and the application of advanced control and protection schemes to ensure system reliability, efficiency, and resilience [37,38]. Distribution systems typically use two main categories of DG sources known as dispatchable and non-dispatchable, as shown in Figure 2.

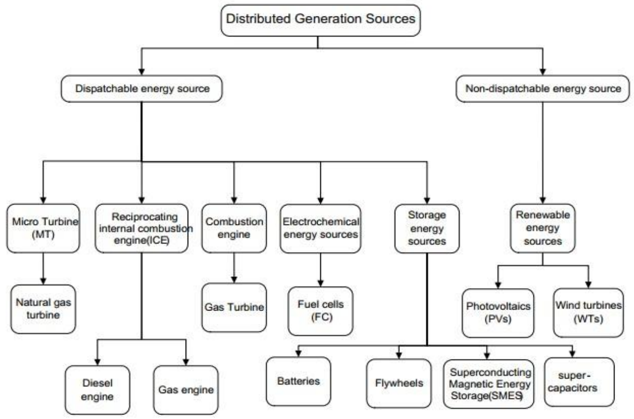

Figure 2: DG Sources

2.1.1 Wind Turbines

Wind energy stands out as one of the most widely utilized sources of DG globally due to its sustainability, scalability, and declining installation costs [41,42]. At the heart of any wind energy system is the wind turbine, a sophisticated device that converts the kinetic energy of wind into usable electrical energy [43,44]. This conversion process begins as wind flows over the turbine blades, causing them to rotate. The rotation drives a shaft connected to a gearbox and an electric generator—typically of the synchronous or induction type—housed within a structure called the nacelle. These generators then transform the mechanical energy into alternating current (AC) electricity, which can be fed into the grid or used locally. A typical wind turbine consists of several key components, including the rotor (which comprises the blades and hub), the main shaft, the gearbox, the generator, and the nacelle that houses most of the turbine's mechanical and electrical components. A coupling mechanism ensures efficient transmission of rotational energy from the blades to the generator [44, 42]. The turbine is mounted on a tall tower, often over 80 meters in height, to access stronger and more consistent wind currents found at higher altitudes.

When multiple wind turbines are strategically installed in a particular area, they form a wind farm. These farms can be located onshore or offshore, depending on geographic and environmental factors [45,46]. Site selection is crucial for maximizing output; areas with high and consistent wind speeds, such as coastal regions, open plains, and mountain passes are typically preferred. To optimize performance, wind farms undergo detailed wind resource assessments using anemometry data and computational models to predict long-term energy production. The power rating of individual wind turbines varies widely, typically ranging from 300 kW to as much as 7 MW, with larger models being used in offshore applications [47]. The overall efficiency of a wind turbine, the ratio of energy captured from the wind to the electrical energy produced, usually falls between 20% and 40%, depending on turbine design, wind speed, and operational conditions [48]. Beyond its technical merits, wind energy offers numerous environmental and economic advantages. As a clean and renewable source, it produces no greenhouse gas emissions during operation and helps reduce dependence on fossil fuels. Financially, wind energy boasts low operational costs and benefits from economies of scale in large wind farm installations. Moreover, advancements in turbine technology and energy storage are making wind power more reliable and cost-competitive compared to conventional and other renewable sources. In summary, wind turbines represent a cornerstone of distributed renewable energy systems [43,48]. Their ability to harness a freely available natural resource and convert it into clean, efficient power continues to drive global interest in wind energy as a sustainable solution to growing electricity demand and environmental concerns.

2.1.3 Photovoltaic Systems

Photovoltaic systems represent a pivotal technology in the field of DG, offering a clean, sustainable means of converting solar energy directly into electricity [49,50]. At the core of any PV system is the solar cell, a semiconductor-based device primarily made from materials such as monocrystalline or polycrystalline silicon [51,52]. These solar cells function similarly to other solid-state electrical components like diodes, transistors, and integrated circuit [43]. A collection of individual solar cells, typically between 36 and 72, is assembled into a solar module or panel, which serves as the basic unit for harnessing solar energy [54]. Solar modules can be connected in series to increase the voltage or in parallel to increase the current, and when multiple modules are interconnected, they form a solar array. These arrays can range in capacity from small-scale units of around 0.3 kW to large-scale installations capable of generating several megawatts of power. This scalability makes PV systems versatile for a wide range of applications, from residential rooftops to utility-scale solar farms [55]. Figure 3 depicts the typical solar generation system as explained above.

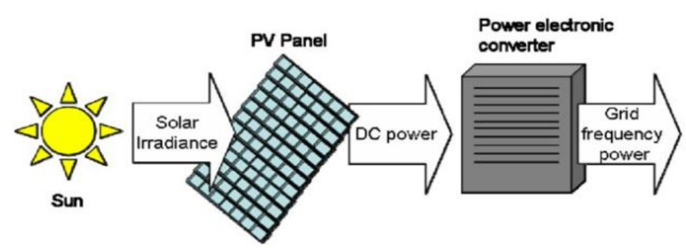

Figure 3: Photovoltaic generation system

Despite their numerous advantages, PV systems are characterized by relatively low energy conversion efficiency when compared to other DG technologies such as wind turbines. Typically, the efficiency of solar modules remains under 20%, although recent advancements in materials and design are pushing this limit higher [56,57]. Nonetheless, one of the key strengths of PV systems lies in their durability and long operational life [58,57]. Most modules have lifespans exceeding 25 years, although their performance gradually diminishes over time, often stabilizing at around 75–80% of their original rated capacity [58,57,60]. To optimize energy harvesting, PV systems utilize power electronic converters equipped with Maximum Power Point Tracking (MPPT) technology [61,62]. These converters ensure that the PV modules operate at their most efficient point under varying irradiance and temperature conditions, thereby maximizing the output power. MPPT converters also facilitate the integration of solar DG units into the grid, ensuring voltage and frequency stability, and supporting bidirectional power flow where necessary [63,64]. Finally, photovoltaic systems are an integral part of modern distributed energy strategies. While they may exhibit lower conversion efficiency compared to wind or hydro systems, their ease of deployment, low maintenance requirements, long service life, and zero-emission operation make them highly attractive for both grid-connected and off-grid applications [65]. As technological innovations continue to improve PV performance and affordability, the role of solar power in distributed generation is expected to grow substantially.

2.1.4 Fuel Cells

Fuel cells are a prominent and efficient technology within the domain of DG, offering a clean and versatile means of producing both electrical and thermal energy through electrochemical reactions rather than combustion [66]. Unlike conventional power generation systems, fuel cells directly convert chemical energy, typically from hydrogen or hydrogen-rich fuels into electricity using a continuous supply of fuel and an oxidant, usually oxygen [67]. This process occurs within a cell composed of two electrodes separated by an ion-conducting electrolyte known as an ionophore, a design similar to that of a battery. However, unlike batteries, fuel cells do not require recharging because the reactants are continuously fed into the system. Fuel cells are notably efficient in electricity generation, with typical electrical efficiencies ranging from 40% to 60%, as shown in Figure 4.

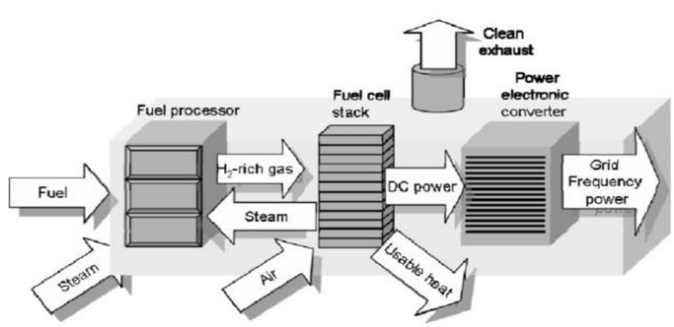

Figure 4: Fuel cell generation system [67]

When used in Combined Heat and Power applications, where the waste heat generated is also utilized, the overall system efficiency can exceed 80% [68]. This high efficiency makes fuel cells particularly attractive for applications requiring reliable and sustainable energy solutions. The power output of fuel cells varies widely depending on their design and intended application. They can deliver as little as 1 kW for residential or small commercial use, or scale up to several megawatts for industrial and utility-scale deployments. Both stationary and mobile configurations are possible, making fuel cells suitable for a diverse range of energy needs [69]. In addition to their efficiency and versatility, fuel cells offer several significant advantages. They operate quietly and have a compact footprint, making them suitable for urban environments or noise-sensitive areas. Most importantly, they emit little to no harmful pollutants, as their primary byproduct is typically water vapor, especially when using pure hydrogen as the fuel source. Furthermore, fuel cells possess a significantly higher energy density over ten times that of traditional batteries enhancing their appeal for applications where space and weight are critical constraints [70]. In summary, fuel cells represent a high-performance, environmentally friendly DG option with the flexibility to serve a wide range of energy applications. Their ability to provide both electricity and heat efficiently, combined with low emissions and modular scalability, positions them as a vital component in the future of clean distributed energy systems. As technological advancements continue to drive down costs and improve fuel cell durability and infrastructure, their adoption in distributed energy networks is expected to expand significantly.

2.1.5 Reciprocating Internal Combustion Engine (ICE)

Reciprocating ICEs, also commonly known as piston engines, are among the most widely used and cost-effective technologies in DG systems [71]. These engines operate on the principle of converting the pressure produced by the combustion of fuel within a cylinder into a rotating mechanical motion through the movement of one or more pistons. The mechanical energy is then used to drive a generator to produce electrical energy [72]. ICE-based DG systems are highly valued for their affordability, operational flexibility, and well-established technological maturity. They are capable of operating on a variety of fuels, including diesel, natural gas, biogas, and gasoline, making them adaptable to local fuel availability and infrastructure. Their rapid startup capability and ability to follow load variations make them ideal for backup power, peak shaving, and even continuous power supply in isolated or weak-grid areas. One of the notable advantages of ICE systems in distributed generation is their ability to be connected directly to the power grid without the need for complex power electronic interfaces. This simplifies integration and reduces system costs, especially when used in conventional grid-support roles. Additionally, ICE systems are modular and scalable, allowing for installations ranging from a few kilowatts to several megawatts, depending on the application [73].

Despite these benefits, ICEs do come with some drawbacks. They produce greenhouse gas emissions and other pollutants, such as nitrogen oxides (NOx) and particulate matter, which pose environmental and regulatory challenges. Moreover, the mechanical nature of the system means that regular maintenance is necessary to ensure reliability and longevity. Finally, reciprocating internal combustion engines remain a dominant force in the DG landscape due to their cost-effectiveness, fuel flexibility, and ease of integration [72,73]. While they may not align fully with long-term sustainability goals due to their reliance on fossil fuels and associated emissions, they continue to play a critical role in current energy systems, particularly where immediate reliability and economic considerations are paramount.

2.3.5 Micro-Turbines

Micro-turbines are small-scale combustion turbines that integrate a compact turbine engine with a high-speed generator to produce electricity and, in some configurations, thermal energy [74]. These systems are typically fueled by natural gas, though other fuels like biogas, propane, and diesel can also be used. Their power output ranges from a few kilowatts up to several hundred kilowatts or more, with some systems scaling into the low megawatt range. One of the defining features of micro-turbines is their ability to operate at extremely high rotational speeds commonly between 50,000 to 120,000 revolutions per minute (rpm)—which is significantly higher than traditional combustion turbines [75,76]. These high speeds allow for compact system design and high power density, making micro-turbines well-suited for distributed generation applications where space constraints are a concern. From a technical standpoint, micro-turbines operate at lower pressures and temperatures than large gas turbines, which contributes to their lower emissions profile and quieter operation. Their emission levels of NO_x and CO_2 are considerably lower, making them an environmentally friendlier option compared to conventional internal combustion engines [77]. Because the electricity generated by micro-turbines is at high frequencies (typically 1500 to 4000 Hz)—well above the standard grid frequencies of 50 or 60 Hz—power electronic converters such as AC-DC-AC inverters are necessary [78]. These converters perform frequency conditioning and synchronization, enabling the output of micro-turbines to be integrated seamlessly into the grid and to operate in parallel with other DG systems as shown in Figure 5.

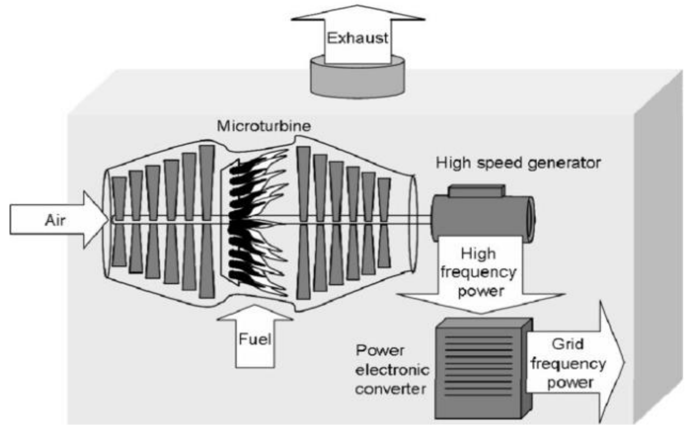

Figure 5: Micro Turbine generation system [74]

Micro-turbines present a range of advantages that make them highly suitable for DG applications. Their compact size and lightweight design allow for easy installation in urban environments and areas with space constraints. With minimal moving parts and the use of air-bearing technology, micro-turbines require low maintenance, reducing operational costs and downtime [74,73]. They also operate quietly, making them ideal for use in residential and commercial settings where noise is a concern. As dispatchable power sources, micro-turbines offer flexible operation and rapid response to fluctuating power demands. Furthermore, they can be configured for CHP applications, achieving overall system efficiencies exceeding 80% by utilizing waste heat for heating or industrial processes. One of their most significant benefits lies in their ability to mitigate the intermittency of renewable energy sources such as solar and wind, making them valuable assets in hybrid microgrid systems. Their integration enhances system stability, improves reliability, and supports dynamic load-following capabilities. Overall, micro-turbines are versatile and efficient DG technologies, particularly well-suited for urban microgrids, remote areas, commercial facilities, and backup systems [74]. As cleaner fuels like biogas and hydrogen become more accessible, the role of micro-turbines in sustainable energy systems is expected to expand significantly.

2.3.6 Role of Energy Storage Devices in Distributed Generation (DG) Systems

Energy storage devices are integral to the functionality of Distributed Generation (DG) systems, particularly in addressing the variability associated with renewable energy sources such as solar and wind. These devices act as critical buffers, balancing energy supply and demand by storing surplus energy during periods of low consumption or high generation and discharging it during peak demand or when generation is low. This balancing function is vital for maintaining system stability, improving power quality, and ensuring continuous and reliable electricity delivery.

The following are common types of energy storage technologies employed in DG systems, each offering unique operational characteristics:

- Batteries: Widely adopted in both grid-tied and standalone renewable systems, batteries (e.g., lithium-ion, lead-acid, sodium-sulfur, and flow batteries) are suitable for medium-duration energy storage, typically from minutes to several hours. Lithium-ion batteries are particularly valued for their high energy density, efficiency, scalability, rapid response, and long operational life, making them popular in modern DG installations.
- Flywheels: These systems store energy in the form of rotational kinetic energy. They offer fast response, high durability, and are best suited for short-term applications such as frequency regulation and voltage stabilization. Flywheels often provide backup power during brief disturbances in DG networks.
- Supercapacitors (Ultracapacitors): Known for their ability to deliver very fast charge and discharge cycles, supercapacitors are effective for short-duration energy support, power conditioning, and bridging short gaps in power supply. However, their lower energy density limits their use in long-duration storage scenarios.
- Superconducting Magnetic Energy Storage (SMES): SMES systems store energy in a magnetic field generated by current flowing through a superconducting coil. They offer exceptionally fast response and high power output, making them ideal for critical power quality applications such as frequency control. Nevertheless, their high cost and the need for cryogenic cooling restrict broader deployment.

Integration of these storage devices into DG networks is typically accomplished through power electronic converters such as inverters, DC-DC converters, and AC-DC-AC interfaces which regulate energy exchange and maintain system voltage and frequency. These interfaces are vital for ensuring the reliable operation of DG systems, especially under variable generation conditions. Beyond energy balancing, storage systems provide numerous operational benefits. They improve load-following capabilities, contribute to peak shaving and valley filling, and enhance energy management efficiency. Moreover, they help mitigate the intermittency of renewables, support grid services such as voltage control, frequency regulation, and black-start functionality, and boost microgrid autonomy, thereby improving overall system resilience. In summary, as the share of renewable energy continues to increase, the role of energy storage in DG systems becomes increasingly essential. When strategically implemented, energy storage technologies enhance the robustness, flexibility, and sustainability of power systems, contributing to the transition toward a cleaner and more reliable energy future.

2.4 Benefits of Distributed Generation

As power systems shift towards decentralization, renewable energy solutions, and sustainability, the role of DG becomes increasingly vital. DG offers significant benefits from both an economic and operational standpoint, balancing costs and advantages to shape the future of energy distribution [81,82].

1. **Economic Benefits**

From an economic perspective, DG provides several key advantages. The most immediate benefit is cost savings. By incorporating DG into the grid, utilities can enhance voltage profiles, improving system efficiency and reducing transmission and distribution losses. This reduction in losses minimizes the need for additional grid infrastructure, resulting in substantial capital expenditure savings. Additionally, DG can lower energy costs by utilizing local energy sources, such as solar or wind, thereby reducing reliance on energy imports from centralized plants [83]. DG systems typically involve lower upfront capital costs compared to large-scale power plants. Their shorter installation timelines further reduce initial investment requirements, making DG an appealing option for both utilities and end-users. This leads to shorter payback periods and higher returns on investment. Furthermore, by aggregating multiple small generators into a larger coordinated system, DG can achieve economies of scale, minimizing transmission line needs and associated maintenance costs. DG also provides ancillary services, such as voltage support, frequency regulation, and congestion relief in transmission networks, further improving grid performance and reducing infrastructure investment needs.

2. **Operational Benefits**

Operationally, DG enhances the reliability and sustainability of power systems. It provides reliable, clean energy, reducing dependence on fossil fuels and improving the environmental footprint of energy systems. Technologies like solar PV, wind turbines, and fuel cells operate with very low emissions, making them attractive for sustainable energy development. A major operational benefit of DG is its ability to reduce the load on the central grid and optimize network configurations. By generating power close to consumption points, DG reduces transmission losses and eases congestion on distribution feeders, leading to a more resilient grid that is less prone to faults and blackouts, improving system stability [84]. DG systems equipped with advanced power electronics and control systems ensure stable voltage profiles, mitigating load fluctuations and maintaining high power quality. These systems can be strategically deployed to minimize network stress and improve overall grid stability. Additionally, DG can be integrated with modern energy storage systems and smart grid technologies to provide essential ancillary services, such as peak shaving, frequency regulation, and black-start capabilities [82,84]. In remote or grid-congested regions, DG offers localized energy generation, reducing the need for extensive transmission infrastructure and directly supplying energy to end-users, enhancing reliability and reducing losses.

3. Strategic Benefits

Strategically placed DG systems can significantly reduce line losses, a crucial advantage of this generation model. By locating DG units near high-demand areas or regions prone to outages, energy distribution can be optimized, reducing the need for long-distance transmission and lowering operational costs. DG also provides the ability to bypass transmission grid congestion, reducing the need for grid upgrades and deferring costly investments in new infrastructure—particularly valuable in regions where existing transmission and distribution systems are nearing capacity. Incorporating DG into modern power systems offers economic, operational, and strategic benefits, enhancing grid efficiency, reducing costs, and improving the reliability and sustainability of electricity supply [82]. By enabling localized generation, DG systems provide the flexibility and resilience needed to support the future grid. However, the effective deployment of DG requires careful planning and strategic placement to maximize transmission loss reduction and optimize system performance. With the right mix of technologies and supporting infrastructure, DG has the potential to transform how energy is generated and consumed.

2.5 Techniques for Reducing Distribution System Losses

In conventional power transmission analysis, load flow computations traditionally utilized the Gauss-Seidel iterative method in combination with the nodal admittance matrix. While this approach was effective initially, further refinements—such as the use of the nodal impedance matrix—have been introduced to improve computational efficiency. Nevertheless, a persistent limitation of the Gauss-Seidel method is its high computational demand, particularly as the number of buses increases. This becomes a significant drawback in distribution systems, which are typically characterized by numerous buses. As a result, the Gauss-Seidel method is not ideal for large-scale distribution networks [85]. Over the past thirty years, the Newton-Raphson (NR) method and its variants have become more prominent, particularly due to their use of sparse matrix techniques and optimal ordering strategies. However, NR methods tend to perform poorly in distribution systems, which often exhibit high resistance-to-reactance (R/X) ratios—conditions under which NR algorithms struggle to converge reliably [86]. To address these challenges, various load flow methods have been developed specifically for distribution networks. Many of these methods are based on the assumption of radial feeder configurations. Among them, the Backward/Forward Sweep (BW/FW) algorithm has gained widespread acceptance for its efficiency and reliability in radial systems. This approach has been employed in the methodology of this study due to its suitability for analyzing distribution networks.

2.5.1 Techniques for Minimizing Losses in Distribution Systems

Energy losses within distribution networks, caused by the transmission of electricity from substations to end-users, represent a considerable source of inefficiency and economic cost. These losses originate from several factors, including resistance in conductors and transformers, as well as charging losses along the transmission lines. In response to growing environmental concerns and the escalating costs of building new power plants, utilities are increasingly focused on optimizing existing infrastructure to accommodate greater loads and reduce delays in power delivery [87]. Loss reduction strategies in distribution systems can be grouped into three major categories:

2.5.2 Minimizing Equivalent Resistance

A fundamental strategy for loss reduction involves decreasing the equivalent resistance of distribution lines. Since power losses are proportional to the square of the current multiplied by the line resistance, reducing resistance can result in notable energy savings [86]. This can be achieved by installing conductors with larger cross-sectional areas, as larger conductors present lower resistance. Alternatively, parallel conductors can be added to share the load. However, practical implementation requires careful cost-benefit analysis, taking into account system demand, installation costs, and the anticipated energy savings.

2.5.3 Installation of Compensating Capacitors

Placing capacitors at strategic load points in the distribution network is an effective method of reducing reactive power flow, thereby minimizing losses. These devices supply reactive power locally, reducing the burden on upstream conductors and improving overall system efficiency. Capacitor installation is particularly beneficial in systems with low power factors, as it contributes to power factor correction and voltage profile improvement [87]. Recent trends favor installing capacitors on primary feeders, where pole-mounted units offer an economical and accessible means of reactive power compensation near inductive loads. Optimal capacitor sizing and placement are guided by factors such as cost, loss reduction potential, and compliance with voltage standards.

2.5.4 Network Reconfiguration

Another technique for reducing system losses involves altering the topology of the distribution network by operating sectionalizing and tie switches. This reconfiguration redistributes electrical loads by transferring power flow from overloaded feeders to those with spare capacity or lower resistance paths [88,89]. The goal is to optimize current paths and reduce I2RI^2R losses. Aside from improving load balancing and voltage profiles, reconfiguration enhances the reliability and operational efficiency of the system. Ongoing research across various utilities continues to explore advanced optimization strategies for feeder reconfiguration.

2.5.5 Distributed Generation (DG) Integration

With the increasing demand for electricity, Distributed Generation (DG) has emerged as a practical alternative to augment supply. DG offers several advantages, including reduced line losses, alleviation of transmission congestion, improved voltage stability, and enhanced system reliability [90]. In addition to lower operational costs, DG units are compact and modular, allowing for quicker deployment and flexible integration into existing infrastructure. Their proximity to end-users addresses challenges such as voltage drops, power quality issues, and excessive loading of transmission lines [91].

When appropriately sited and sized, DG units can significantly reduce system losses and enhance overall efficiency. Their adaptability makes them especially suitable for decentralized systems with variable demand. However, optimal placement and sizing require robust analytical tools and optimization models to ensure maximum benefit while maintaining system stability.

Table 2: The Summary of the Related Reviewed Work

Author (s)	Focus	Gaps
Ahiakwo et al., (2020)	Optimization of EGI-Clan 33kv Power Distribution System for Improved Performance	The study lacks analysis of dynamic and transient conditions, limiting its applicability to real-world power system operations involving fluctuations and disturbances
Kalajahi et al., (2020)	Optimization of EGI-Clan 33kV power distribution system performance using power flow algorithms and Newton-Raphson load flow solutions.	The study's findings are specific to a particular distribution system, limiting their generalizability to other networks with different configurations.
Okorie et al., (2021)	Optimization of Energy Efficiency for Electric Power Distribution System Losses.	The focus on 3 study areas restricts the applicability of its findings to broader or differently configured power systems.
Aneke, (2021)	Improving Loss Minimization in 33kv Power Distribution Network Using Optimized Genetic Algorithm.	The study's limited 2.1% improvement reveals that OGA alone may be insufficient, highlighting the need for more advanced or hybrid optimization methods to effectively tackle power grid instability.
I. Musa et al., (2021)	Integration of DG using Small Population PSO (SPPSO) for power loss reduction and voltage profile improvement in 33 and 69-bus systems.	While SPPSO reduces computational complexity, the study does not consider dynamic load variations or real-time implementation challenges.
Ehimen et al., (2022)	Modeling of Existing 330kV and Meshed 330kV Super-grid Transmission Line for the Nigerian Network.	The study lacks a comparison with alternative network configurations and does not address the practical challenges, costs, or scalability of implementing a meshed network in real-world systems.
Pan et al., (2023)	Two-stage optimization for DG placement and reactive power supply to minimize power losses in IEEE 15 and 33-bus systems.	The approach is tested only on standard test systems; applicability to real-world, larger-scale networks remains unaddressed.
Manandhara et al., (2023)	Combined network reconfiguration and DG integration using Artificial Bee Colony (ABC) algorithm for loss minimization and voltage profile enhancement.	The study lacks a comparative analysis with other metaheuristic algorithms and does not consider the economic aspects of implementation.
Joshi, (2023)	An Analysis of Reliability-Technical Losses In 33 kV Radial Distribution/transmission system In Far Western Region of Nepal.	The study does not assess the scalability of the proposed approach in larger systems or its performance under dynamic conditions, which are essential for real-world applications and long-term reliability.
Adegoke et al.,(2024)	Optimal placement and sizing of DG using Particle Swarm Optimization (PSO) to minimize power losses in a 34-bus distribution network.	The study focuses on a single DG unit and does not explore the impact of multiple DG placements or varying load conditions.
Ermiyas,(2024)	Comparative study of optimization methods (ABC, PSO, GA) for 33kV distribution network feeder reconfiguration focusing on power losses and voltage profile.	The research does not incorporate real-time data or adaptive algorithms that respond to changing network conditions.

Table 2 presents a summary of the reviewed related literature along with the identified research gaps, highlighting opportunities for future research and guiding subsequent scholarly investigations.

3.0 Research Findings

The review reveals a compelling narrative on the transformative potential of Type C Distributed Generation (DG) units, particularly solar photovoltaic (PV) systems, in enhancing Medium Voltage (MV) distribution networks. As global electricity demand surges and grid infrastructures age, the need for decentralized, intelligent, and sustainable energy solutions becomes urgent. Type C DG systems, although non-dispatchable, offer scalable and low-emission alternatives to traditional generation. Their integration into MV networks operating typically between 11 kV and 33 kV addresses pressing challenges such as active power losses, voltage instability, and grid inflexibility, especially within conventional radial configurations. While PV systems exhibit relatively lower efficiency compared to wind or hydro sources, advances in materials, power electronics, and Maximum Power Point Tracking (MPPT) have significantly enhanced their performance and grid compatibility. Furthermore, the synergy between PV systems and emerging storage technologies, like lithium-ion batteries and flywheels, strengthens the role of DG in mitigating intermittency and ensuring voltage and frequency stability. The review highlights that optimal siting and sizing of DG units, guided by advanced optimization algorithms, are critical to maximizing their impact. Overall, the findings underscore that smart, strategic deployment of Type C DG can reduce system losses, improve power quality, and pave the way for resilient, future-ready smart grids

4.0 Conclusion

This comprehensive review underscores the transformative role of Type C Distributed Generation (DG) units particularly solar photovoltaic (PV) systems in modernizing and enhancing the performance of Medium Voltage (MV) distribution networks. As global energy systems pivot toward sustainability, the strategic integration of these non-dispatchable, renewable energy sources emerges not just as an environmental imperative, but as a technically sound and economically viable solution to address critical issues like voltage instability, power losses, and operational inflexibility in conventional radial networks. Despite inherent challenges such as intermittency and integration complexity, innovations in smart inverters, Maximum Power Point Tracking (MPPT), and energy storage technologies are steadily improving the grid compatibility and operational efficiency of Type C DG units. When optimally sized and sited, these systems can significantly improve voltage profiles, reduce active power losses, and enhance overall system resilience especially in regions where aging infrastructure and load variability compromise reliability. Furthermore, the deployment of Type C DG units supports the evolution of legacy distribution networks into future-ready smart grids. By fostering bidirectional power flows and enabling localized generation, these technologies reduce the dependence on centralized power plants and create new paradigms for energy democratization, cost reduction, and environmental stewardship. Finally, while technical, regulatory, and economic hurdles remain, the integration of Type C DG spearheaded by solar PV is a forward-looking strategy capable of redefining energy distribution paradigms. Continued research, policy support, and investment in optimization algorithms and grid-interactive technologies are essential to unlock the full potential of DG in achieving resilient, efficient, and sustainable power systems worldwide.

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Conflict of interest

All the authors declared no conflict of interest.

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