

Review article

Navigating the complexities of distributed generation: Integration, challenges, and solutions

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ABSTRACT

In recent years, the landscape of power generation has undergone a significant transformation, moving from centralized power plants to decentralized power systems. This shift has been driven by substantial changes in grid architecture, introducing the concept of Distributed Generation (DG), which is now a vital component of electrical power systems, especially within distribution networks (DNs). Integrating DG is crucial for ensuring reliable power generation and reducing power losses. However, the widespread adoption of decentralized technologies presents new challenges for power systems, such as identifying optimal locations for DG installation, configuring protective devices, managing voltage control, and addressing Power Quality (PQ) issues. The variability and unpredictability of Renewable Energy Sources (RES), such as solar and wind power, add to these complexities, requiring careful evaluation and strategic planning. This research's primary contribution lies in its thorough exploration and systematic analysis of various DG types and their integration methods. By identifying and addressing the key challenges of DG integration, this study offers valuable insights and innovative solutions that enhance grid stability and efficiency. Furthermore, the research proposes strategic frameworks for optimal DG deployment, advanced control strategies, and effective regulatory compliance, which are essential for the sustainable development of electrical power systems. The findings underscore the importance of adopting holistic approaches to address the complexities of DG integration, ultimately contributing to a more resilient and sustainable energy future.

1. Introduction

The global surge in electrical demand has necessitated a significant expansion in the capacity of electric power plants. This increased demand has led governments in developed nations to adopt strategies to minimize load curtailment. Issues related to power losses and voltage fluctuations have become more prominent, particularly due to the considerable distance between power generation facilities and major

load centers. One promising solution to these challenges is the strategic placement of DG units near distribution substations (Muthukumar and Jayalalitha, 2016).

The growing recognition of renewable DG units as viable alternatives to traditional power stations presents substantial opportunities to meet the escalating electricity demand. Globally, the capacity of renewable energy sources (RES) increased by 8.3 % within a single year, rising from approximately 2000 GW in 2016–2167 GW in 2017 (Petinrin and

Abbreviations: CAES, Compressed-Air Energy Storage; CHP, Combined Heat and Power; DFIG, Doubly-fed Induction Generators; DOCRs, Directional Overcurrent Relays; DR, Distance Relay; D-STATCOM, Distributed Static Synchronous Compensators; FACTS, Flexible AC Transmission Systems; FCL, Fault Current Limiter; FLDM, Fuzzy Logic Decision Making; FRDFT, Fast Recursive Discrete Fourier Transform; GPS, Global Positioning System; ITSS, Ice-thermal Storage System; LP, Linear programming; NLP, Non-Linear Programming; OLTC, On-Load Tap Changer; PCC, Point of Common Coupling; PCI, Protection Coordination Index; PDS, Power Delivery System; PEVs, Plug-in Electric Vehicles; PHEVs, Plug-in Hybrid Electric Vehicles; SCL, Short-Circuit level; SED, Smart Electronic Device; STATCOM, Static Synchronous Compensator; SVC, Static Var Compensator; SVC, Static Var Compensators; TPNLP, Two-Phase Non-Linear Programming; V2G, Vehicle-to-Grid; VSC, Voltage Source Converter; WG, Wind Generator.

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Shaaban, 2016). This diverse array of renewable and conventional DG options includes wind generators (WGs), solar thermal systems, photovoltaic (PV) arrays, hydroelectric generators, combustion engines, hydrogen fuel cells, geothermal plants, and microturbines (Nanda et al., 2024; Alsharif et al., 2016). Factors such as rising power demand, the necessity for energy storage, and growing concerns about global climate change have driven a surge in DG system deployments, which hold the potential for significant reductions in carbon emissions over time. However, integrating substantial DG units into electricity generation networks brings both advantages and potential drawbacks, particularly regarding voltage and frequency regulation and protection mechanisms (Alsharif, 2017; Firouz et al., 2014; Sun et al., 2024). The benefits of adopting DG systems are significant and include:

- **Reduced Power Outages:** Proximity between power demand and generation sources mitigates the incidence of power outages.
- **Reduced Fossil Fuel Dependency:** There is a significant reduction in reliance on fossil fuels for energy generation.
- **Lower Greenhouse Gas Emissions:** There is a substantial decrease in the emission of greenhouse gases.
- **Deferred Expansion Investments:** The need for investments in expanding transmission systems is deferred.
- **Enhanced Power Quality:** The integration of power converter-based DG systems improves power quality.
- **Diminished Voltage Losses:** Voltage losses are reduced, leading to improved voltage profiles.
- **Improved Network Reliability:** The overall reliability of the power network is enhanced (Archana et al., 2016).

Fig. 1 provides a visual representation of advantages of DG

integration. The implementation of DG systems presents a broad spectrum of advantages in terms of reliability, sustainability, and efficiency within power generation and distribution. One notable advantage of DG is its capability to serve as a standby power supply when the primary grid is absent, potentially enhancing power quality in distribution networks (DNs) (Javadian et al., 2013a). However, addressing the challenges related to proper unit sizing and location within DNs is critical, as improper placement can lead to significant technical complications, such as affecting voltage levels, power source reliability, system performance, asset management, protection systems, and the occurrence of undesired islanding (Alsharif et al., 2016; Manditereza and Bansal, 2016).

From an economic perspective, incorporating DG can impact the revenue structure of distribution companies, which often provide grid access to DG units to offset a portion of their operational expenses. The inclusion of DG units in the network could potentially jeopardize this revenue stream. Furthermore, DG introduces an element of unpredictability, necessitating the adoption of an efficient and economical energy management system (Manditereza and Bansal, 2016; Karatepe et al., 2015). It is crucial to consider the time-variable nature of DG power output when used as standby units. In practice, DG units are often sited in locations with high demand or near the endpoints of feeders in radial networks, ensuring optimal utilization and potential benefits for both local load requirements and overall system performance.

The implementation of DG systems holds significant potential, provided that challenges related to optimal sizing, location, technical issues, and economic impacts are effectively addressed. DG systems can serve as reliable backup power sources, and their time-variable nature underscores the necessity for robust energy management systems. With meticulous planning and strategic deployment, DG systems can

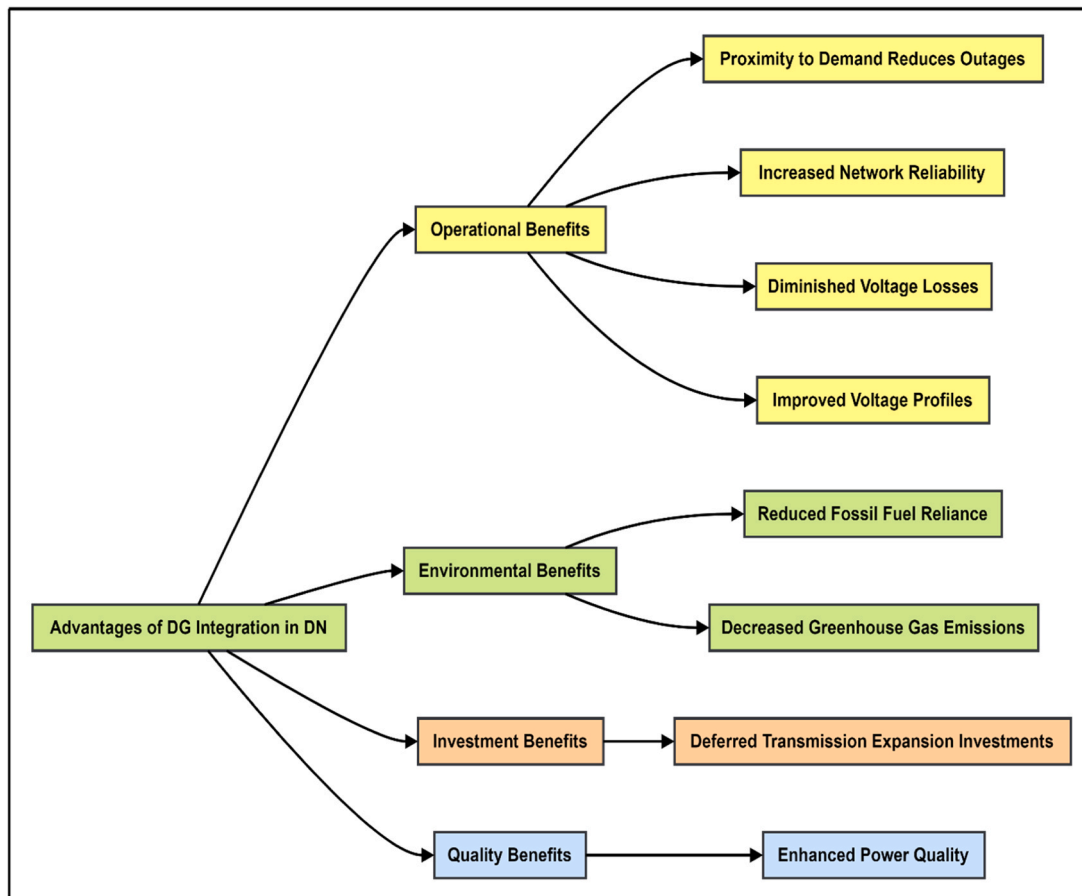


Fig. 1. Advantages of DG integration the distribution system.

Table 1
Comparison of technological solutions for RES uncertainty compensation.

Category	Operational Characteristics	Impact on DN	Examples	Applications and Benefits
DG with Active Power Injection	Injects active power into the DN using power electronic interfaces (e.g., PV arrays, microturbines)	Seamless integration with the grid, contributes to unity power factor, compact size, efficient power injection	PV arrays, microturbines, fuel cells, batteries	Provides local power generation, reduces transmission losses, supports grid stability
Reactive Power Injection DG	Provides reactive power support (e.g., synchronous compensators)	Focuses on voltage stability, power factor control, enhances overall stability of the DN	Synchronous compensators	Mitigates voltage fluctuations, improves power factor, supports grid reliability
Generation of Active Power and Consumption of Reactive Power by DG	Induction generators (e.g., DFIG in wind generators)	Actively injects electrical energy while absorbing reactive power, maintains PQ within the DN	DFIG in wind generators	Efficient energy conversion, grid support during variable renewable energy generation
DG with Simultaneous Active and Reactive Power Injection	Synchronous machines (e.g., steam turbines, CHP units)	Injects both active and reactive power into the DN, enhances grid stability and PQ	Steam turbines, CHP units	Provides combined heat and power generation, enhances grid reliability and stability

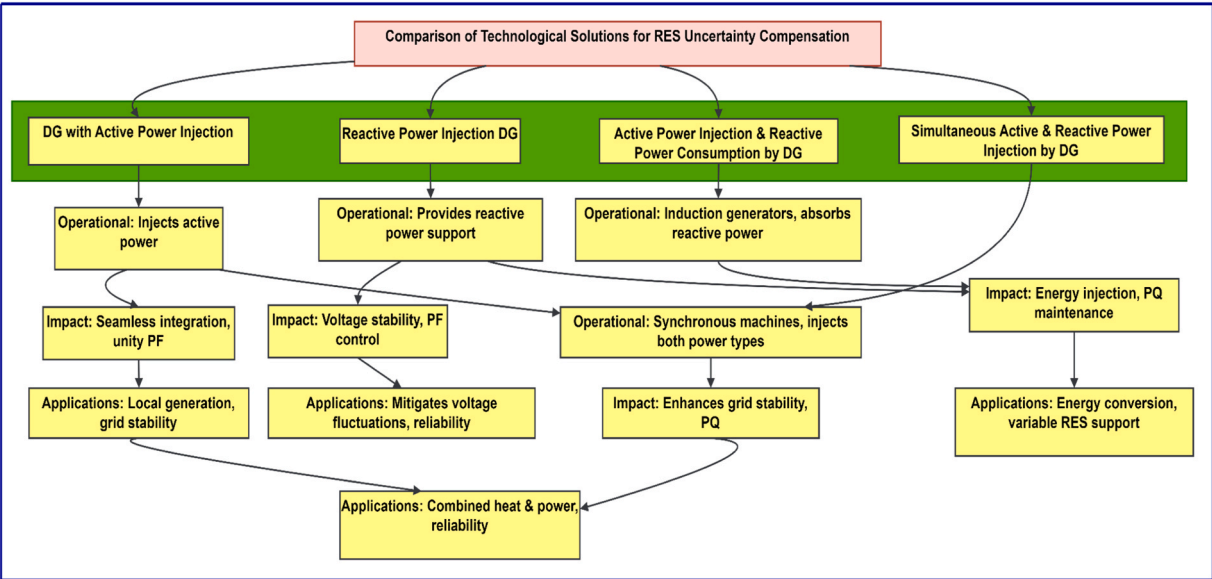


Fig. 2. Classification of various types of DGs.

significantly transform power distribution by enhancing reliability, promoting sustainability, and improving overall efficiency in energy networks. The system’s characteristics are shaped by various factors, including the architectural configuration and the inherent variability in power generation from DG units. The strategic placement of DG units in radial DNs can lead to substantial benefits, such as improved voltage profiles, reduced congestion, decreased peak load demand on feeders, and lower greenhouse gas emissions from non-renewable energy sources (Rajaram et al., 2015).

DG units are critically important in DNs, transforming traditionally passive systems into active components of the electrical grid. This transformation provides several advantages, including deferred investment in new infrastructure, improved system reliability, and reduced peak demand for electricity (Bagheri et al., 2015; Bayat et al., 2016). A comprehensive review highlighted the drivers, benefits, and challenges associated with integrating renewable energy-based DG systems into DNs. DG units affect the direction of energy flow and the magnitude of short-circuit currents within DNs. A significant consequence of DG integration is the increased short-circuit current levels, which can contribute to fault currents during downstream failures. This increase can reduce the relative contribution of DG units to the overall fault current, potentially compromising the effectiveness of the existing protection schemes (Hou et al., 2024; Zahedi, 2011a).

An example of this issue is the inadvertent tripping of protective devices caused by faults in nearby distribution lines with DG integration. The strategic placement of DG units, along with considerations of their

number and integration level, substantially impacts the effectiveness of protection schemes [6, 11, and 18]. This study investigates the complex interaction between DG units and power systems, examining their dynamics from a technological perspective. The integration of DG units into conventional DNs offers several benefits, including reduced energy losses and improved operational efficiency. However, it also presents challenges, such as potential threats to network reliability and concerns regarding the integrity of protection systems. To fully leverage the benefits of DG units while mitigating associated risks, it is essential to thoroughly understand the implications of DG integration within DNs. This is especially critical in light of the increasing adoption of sustainable energy generation practices, which are primarily implemented at the distribution level (Riad et al., 2024).

This research undertakes a detailed examination of the intricate relationship between DG units and DNs, aiming to identify both the advantages and challenges posed by the shift towards greener energy generation. It also explores existing solutions to pertinent challenges, focusing on voltage control techniques within the context of DG integration and their impact on protection systems. These considerations are particularly relevant given the advancements in modern smart grid technologies.

The paper is systematically organized to address various aspects of DG and its effects on DNs.

Section 2 begins with a comprehensive examination of the different types of DG systems, offering an in-depth look at their distinct characteristics, operational mechanisms, benefits, and limitations. This

Table 2
Key parameters for integrating DG into DN.

Parameter	Description
Type(s) of DG resources integrated	This parameter refers to the specific types of distributed generation (DG) resources that have been integrated within the distribution network (DN). DG resources can include renewable energy sources such as solar photovoltaic (PV) systems, wind turbines, and biomass generators, as well as non-renewable sources like diesel generators and micro-turbines. Understanding the types of DG resources helps in assessing their suitability, performance, and impact on the grid.
Initial generation level	This denotes the initial capacity at which the DG units were connected to the grid. It is important to document the starting generation level to evaluate the scalability and growth potential of DG resources. The initial generation level also aids in analyzing the incremental impact on the grid as more DG units are added.
Designated voltage level	This parameter specifies the voltage level at which DG components are interconnected with the grid. The designated voltage level is crucial for ensuring compatibility and seamless integration of DG resources with the existing grid infrastructure. It also influences the design and selection of interconnection equipment and protection devices.
Electrical stability at interconnection point	This refers to the inherent electrical stability at the point where the DG units are connected to the grid. Electrical stability includes aspects such as voltage regulation, power quality, and the ability to maintain steady operation under varying load conditions. Stability at the interconnection point is vital for preventing disturbances and ensuring reliable grid operation.
DG unit capacity relative to grid load	This parameter measures the capacity of DG units relative to the overall load of the grid. It helps in understanding the contribution of DG resources to the total power demand and their potential to offset grid supply. A balanced capacity relative to grid load ensures that DG units can effectively support the grid without causing overloading or underutilization.
Grid susceptibility to short circuits	This denotes the susceptibility of the grid to short circuits at the installation site of DG units. High susceptibility to short circuits can pose safety risks and lead to equipment damage. Assessing this parameter helps in designing appropriate protection schemes and mitigating measures to enhance grid resilience.
Impact on grid frequency	This parameter evaluates the effect of DG integration on the stability and regulation of grid frequency. Maintaining a stable grid frequency is essential for the synchronized operation of the power system. DG resources, especially those with variable output like wind and solar, can influence frequency stability. Understanding this impact is crucial for implementing effective frequency control strategies.
Control mechanisms	This refers to the methods and systems in place to control the output of DG units and their interactions with the grid. Control mechanisms can include automated systems, real-time monitoring, and feedback loops to adjust DG output based on grid conditions. Effective control mechanisms ensure optimal performance, grid stability, and efficient utilization of DG resources.
Integration challenges	This parameter outlines the specific challenges encountered during the integration of DG resources into the grid. Challenges can range from technical issues such as grid compatibility and interconnection standards to regulatory hurdles and operational constraints. Documenting integration challenges helps in developing solutions and best practices for future DG projects.
Regulatory compliance	This denotes the adherence to regulatory standards and requirements for the integration of DG

Table 2 (continued)

Parameter	Description
	resources. Regulatory compliance ensures that DG installations meet safety, performance, and environmental standards. It also involves obtaining necessary permits and approvals from relevant authorities. Compliance with regulations is essential for the legal and safe operation of DG units within the grid.

foundational section provides a clear understanding of the various DG technologies available.

Section 3 explores the implications of varying levels of DG penetration on DNs. It assesses how increasing the proportion of DG units within a distribution network can influence overall network performance, stability, and efficiency. The analysis includes both the potential advantages, such as enhanced network reliability and reduced energy losses, as well as the challenges that arise, particularly concerning voltage regulation and power quality.

Section 4 addresses the complexities associated with voltage control in networks that integrate DG units. It investigates the impact of DG on traditional voltage control methods and discusses their limitations. The section also proposes advanced techniques and solutions for maintaining voltage stability in the face of increased DG presence.

Section 5 turns its attention to the challenges faced by protection systems when DG units are integrated into distribution networks. It examines how DG influences existing protection schemes, including issues related to fault detection, coordination, and relay settings. The discussion highlights the need for updated protection strategies and technologies to effectively manage the dynamic nature of networks with significant DG penetration.

Section 6 concludes by synthesizing the observations and insights derived from the preceding sections. It summarizes the key findings of the study and offers relevant conclusions. This concluding section aims to provide a cohesive overview of the study’s contributions and suggest potential avenues for further research and practice in the field of DG integration.

2. Classification of DGs

DGs can be systematically categorized into distinct groups as delineated in (Riad et al., 2024), based on the provision of active and reactive power to the DN. This classification forms the foundational framework for understanding the discussions that follow in this paper. Table 1 delineates various categories of DG, distinguishing them based on their operational characteristics and their impact on the DN. Fig. 2 provides a detailed classification of different types of DG technologies. The figure categorizes DG units based on their power sources, operational characteristics, and integration methods within the distribution network.

DG systems exhibit a range of critical parameters that influence their integration with the grid (Alsharif et al., 2016). Notably, the dimensions of DG units can significantly vary in terms of their energy capacity, spanning from small-scale power outputs of a few kilowatts to substantial magnitudes reaching multiple megawatts (Prakash and Khatod, 2016; Karatepe et al., 2015). Table 2 provides an outline of the critical parameters involved in the integration of distributed generation resources within distribution networks. Each parameter is crucial for ensuring the effective, stable, and compliant integration of DG into the grid. A thorough understanding of these factors is imperative to address the challenges and optimize the benefits associated with the deployment of DG.

3. Various aspects of DG integration

Before exploring the impact of DGs on power DNs, it is imperative to examine various facets of their integration. The following points

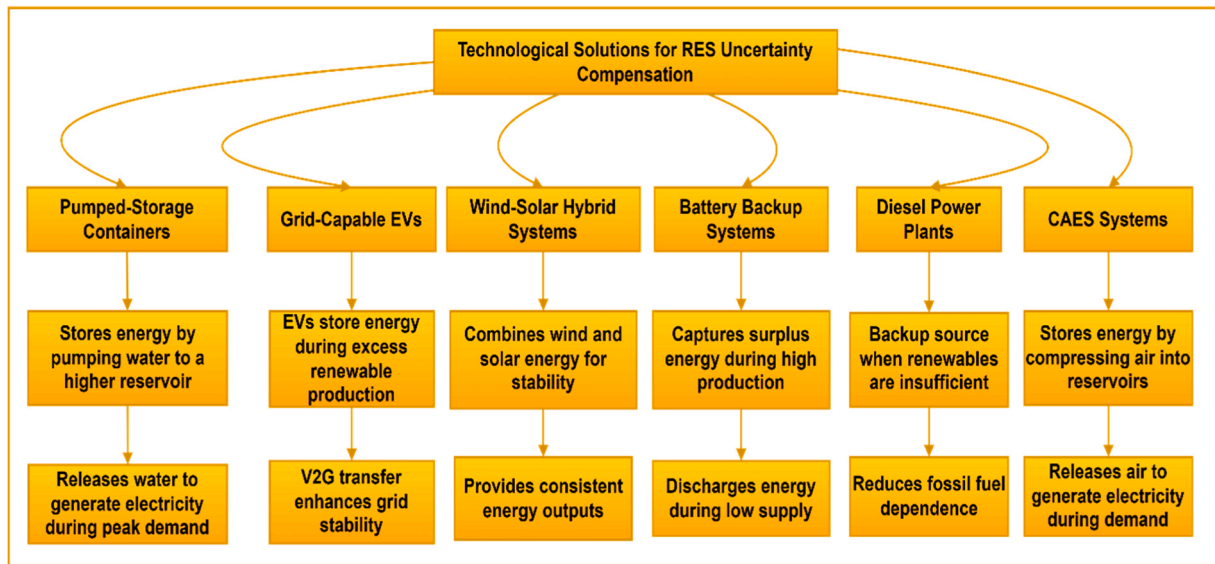


Fig. 3. Technological solutions for the compensation of uncertainties of RES based system.

Table 3

Comparison of technological solutions for mitigating RES uncertainties.

Function / Benefit	Pumped-Storage Containers	Grid-Capable Electric Cars	Wind-Solar Hybrid Systems	Battery Backup Systems	Diesel Power Plants	CAES
Energy Storage	✓	✓		✓	✓	✓
Load Balancing	✓			✓	✓	✓
Grid Support		✓			✓	
Enhanced Grid Stability	✓	✓	✓		✓	✓
Efficient Use of Renewable Energy	✓					
Peak Shaving	✓			✓		✓
Integration into Renewable Ecosystem		✓				
Reduced Intermittency			✓			
Stable Energy Output			✓			
Enhanced Resource Utilization			✓			
Reliable Power Supply		✓		✓	✓	
Smooth Transition During Fluctuations		✓		✓	✓	
Demand Response		✓				
Backup During Low RES Production				✓	✓	
Reduced Environmental Impact					✓	✓
Equation	$E_s = \eta \cdot m \cdot g \cdot h$	$E(EV) = \eta(EV) \cdot C(EV)$	$P_{\{hybrid\}} = P_{\{wind\}} + P_{\{solar\}}$	$E_{\{bat\}} = C_{\{bat\}} \cdot V_{\{bat\}} \cdot \eta_{\{bat\}}$	$P_{\{diesel\}} = P_{\{fuel\}} / F_{\{eff\}}$	$E(CAES) = P_{\{compressor\}} \cdot \frac{t}{\eta_{\{compressor\}}}$
Explanation	Energy stored in the upper reservoir based on efficiency (η), mass of water (m), gravity (g), and height difference (h).	Energy available from EVs based on the efficiency η (EV) and battery capacity C (EV).	Total power output is the sum of wind power ($P_{\{wind\}}$) and solar power ($P_{\{solar\}}$).	Energy stored in a battery using capacity ($C_{\{bat\}}$), voltage ($V_{\{bat\}}$), and efficiency ($\eta_{\{bat\}}$).	Power output based on fuel power $P_{\{fuel\}}$ and generator efficiency $F_{\{eff\}}$.	Energy stored based on compressor power ($P_{\{compressor\}}$), time of compression (t), and compressor efficiency ($\eta_{\{compressor\}}$).

Table 4
Benefits of incorporating DG within Electrical Distribution Networks.

Parameter	Description	Benefits	Example or Impact
Enhanced System Efficiency	Improved overall system efficiency through effective utilization of energy resources.	Optimal use of available energy resources, reduced energy losses.	Increased system reliability, reduced waste heat.
Reduced Operational Costs	Reduction in peak load demand leads to lower operational expenses during high demand periods.	Lower electricity bills, decreased need for additional infrastructure.	Cost savings, improved financial performance.
Economical Maintenance	Lower maintenance costs due to a conducive operating environment facilitated by DG adoption.	Extended equipment lifespan, fewer repairs required.	Reduced downtime, enhanced equipment reliability.
Decreased Maintenance Expenditures	Reduced maintenance requirements resulting from improved system conditions with DG implementation.	Lower labour and material costs, streamlined maintenance operations.	Enhanced asset management, improved asset longevity.
Mitigated System Expansion Costs	Alleviates the need for extensive system expansion, thereby lowering associated expenditure.	Avoided capital investments, deferred infrastructure upgrades.	Financial flexibility, optimized capital allocation.
Enhanced Load Protection	Strengthened protective measures for handling heavy loads, ensuring system stability and reliability.	Improved grid stability, enhanced resilience against disturbances.	Reduced risk of blackouts, improved customer satisfaction.
Diminished Demand and Expenses	Mitigation of peak loads and enhanced system stability lead to reduced demands and related costs.	Reduced peak demand charges, optimized resource allocation.	Lower energy procurement costs, improved load management.
Lowered Fuel Costs	Decreased dependency on conventional fossil fuels results in reduced fuel expenses.	Savings on fuel purchases, reduced exposure to fuel price volatility.	Environmental benefits, improved energy independence.

enumerate some of the common challenges associated with the placement of DGs:

3.1. Uncertainties following DG integration

One of the significant characteristics of integrating RES-based DG into power grids is the intermittent nature of energy generation. This implies that the electrical output capacity of RES-integrated DG units can fluctuate unexpectedly over time. Predicting the energy production of certain technologies, such as wind turbines and PV systems, is challenging due to their reliance on meteorological conditions, which inherently lack predictability (Karatepe et al., 2015; Rajaram et al., 2015; Saxena et al., 2021a).

In the domain of solar energy, unreliability arises from a variety of unpredictable factors that are not consistently present. Historical data can partially mitigate this inherent drawback in specific contexts; however, forecasts related to solar irradiation often exhibit a considerable degree of inaccuracy. In contrast, wind energy is particularly notable for its high degree of uncertainty, due to its inherently fluctuating and unstable density. The deployment of wind DG units can be inconsistent and sporadic in certain regions, as highlighted in reference

(Bhide and Monroy, 2011). This variability impedes the application of predetermined frameworks for generation. Consequently, addressing this challenge necessitates the adoption of probabilistic approaches to resolve conflicts in generation scheduling. The intermittent nature of wind energy exacerbates issues related to generation scheduling and introduces concerns about the overall protection of the system, as discussed in reference (Saxena et al., 2023). It is important to emphasize that the evolving landscape of RES has introduced competitive alternatives to conventional generation technologies, largely driven by the significant decline in costs witnessed over the past few decades.

The International Renewable Energy Agency (IRENA) has projected a substantial decline in the capital costs associated with onshore wind turbines. Specifically, IRENA's analysis indicates a remarkable 66 % reduction in capital costs between 2014 and 1983, with an additional 12 % cost reduction anticipated by the year 2025 (Taylor et al., 2016). These cost trends underscore not only the economic viability of wind energy but also contribute to the changing dynamics of the energy sector, fostering a transition towards more sustainable and cost-effective energy generation methods. Incorporating supplementary equipment alongside DG units presents a viable approach for mitigating the impact of uncertainties associated with RES. Below are several illustrative examples of potential technological solutions that could serve as effective compensators for RES uncertainties:

Table 5
Challenges and mitigation strategies for DG integration.

Parameter	Challenge	Impact	Mitigation Strategies
Re-closing Events	Potential for disjointed re-closing events	Risk of equipment damage and safety hazards	Coordinated re-closing schemes
Automatic Closure	Complications in preventing automatic closure	Unintended energizing of disconnected segments	Advanced control algorithms for closure prevention
Islanding Scenarios	Unintentional islanding scenarios	Safety risks and regulatory non-compliance	Islanding detection techniques
Short-Circuit Contributions	Fluctuating short-circuits contribution levels	Inconsistent protection system response	Adaptive protection settings
Protection System Effectiveness	Impaired effectiveness of protection systems	Reduced reliability and increased fault duration	Enhanced protection schemes
Generator Stability	Occurrences of generators tripping unintentionally	Loss of generation capacity and stability issues	Improved generator protection coordination
Feeder Protection	Diminished performance of feeder protection mechanisms	Increased fault impact and extended outage duration	Feeder protection system upgrades

- **Pumped-Storage Containers:** Pumped-storage containers are recognized as a promising solution for storing excess energy generated from renewable sources during periods of high availability (Muthukumar and Jayalalitha, 2016). This innovative method involves transferring water from a lower to a higher elevation reservoir when energy production exceeds immediate demand. Subsequently, the stored water is released from the upper reservoir to drive turbines and generate electricity during peak consumption periods.
- **Grid-Capable Electric Cars (PEVs and PHEVs):** Electric vehicles equipped with grid capabilities, such as PEVs and PHEVs, can function as portable energy storage devices (Petinrin and Shaaban, 2016). These vehicles recharge during periods of excess renewable energy generation and can supply stored energy back to the grid as needed. This bidirectional energy transfer, known as V2G, enhances grid stability and resilience.
- **Wind-Solar Hybrid Systems:** Hybrid systems combining wind and solar energy sources offer improved stability and enhanced utilization of renewable resources (Nanda et al., 2024). By leveraging diverse weather conditions, these systems provide more consistent energy outputs, thereby mitigating the intermittency associated with individual renewable sources.
- **Battery Backup Systems:** Battery backup systems act as short-term energy storage solutions that capture surplus energy during times

Table 6
Strategies for enhancing stability and protection of DG systems.

Strategy	Description	Key Elements	Purpose	Challenges	Ref.
Swift Response to Error	Immediate deactivation of the DG upon error detection to minimize system impact	Error detection, prompt deactivation	Minimize impact of errors on the system	Ensuring reliable error detection and rapid response	(Wan et al., 2010; Ma et al., 2010; Baran and El-Markabi, 2004)
Capacity Restriction	Limiting the DG capacity to prevent overloading and instability	Capacity cap, controlled power contribution	Prevent overloading and instability due to excessive power	Determining optimal capacity limits, maintaining efficiency	(Kumar et al., 2016; Liu et al., 2015)
Adaptive Protection Method	Ensuring the protection scheme remains responsive to changing network conditions	Adaptive protection, responsiveness to evolving conditions	Maintain protection effectiveness under varying conditions	Implementing adaptable and cost-effective protection schemes	(Brahma and Girgis, 2004; Shen et al., 2017)
Enhanced Protection Scheme	Upgrading the protection scheme with advanced devices	DOCRs integration, DR, circuit breakers, re-closers, network reconfiguration, auxiliary devices	Improve overall protection and reliability of the DG system	Managing integration of multiple protection devices	(Zeineldin et al., 2013, 2015; Nikolaidis et al., 2016), (Sinclair et al., 2014; Chilvers et al., 2005)
FCL Integration	Incorporation of Fault Current Limiters to control fault currents and enhance stability	FCL devices, fault current control	Control fault currents, enhance system stability	Selecting appropriate FCLs, ensuring compatibility with existing systems	(El-Khattam and Sidhu, 2008; Yamaguchi and Kataoka, 2008; Zhang and Dougal, 2011)

of high production and discharge it during periods of low supply (Alsharif et al., 2016). These systems provide immediate support during fluctuations in renewable energy availability, ensuring continuous power delivery.

- **Diesel Power Plants:** Diesel power plants serve as backup sources of energy when renewable energy production is insufficient (Alsharif, 2017). These plants offer reliable power supply, reducing dependence on fossil fuels and enhancing grid stability during peak demand periods.
- **CAES Systems:** CAES systems store surplus energy by compressing air into underground reservoirs, which can later be released to generate electricity during periods of increased demand (Firouzi et al., 2014). CAES technology contributes significantly to grid stability by mitigating fluctuations in renewable energy sources.

Fig. 3 illustrates various technological solutions designed to address uncertainties associated with RES. These solutions aim to mitigate the variability and intermittency inherent in RES-based systems.

Table 3 compares various technological solutions based on their functions and benefits in addressing uncertainties associated with RES. Evaluating each technology's capabilities and contributions helps identify effective strategies for enhancing grid stability, efficiency, and reliability.

3.2. Advantages of DG integration

From ecological, financial, and technological standpoints, multiple facets of integrating DG into power systems warrant consideration (Prakash and Khatod, 2016). Notably, RES constitute a significant portion of DG deployment in countries like Germany, Denmark, and Sweden (Anaya and Pollitt, 2015), especially as non-renewable petroleum resources become increasingly scarce. Given that fossil fuel consumption is a leading contributor to pollution emissions, the adoption of environmentally friendly DG units emerges as a prospective strategy for addressing global warming (Kefayat et al., 2015).

To fully grasp the financial benefits of DG implementation, it is essential to conduct a comprehensive assessment of its inherent advantages. Several studies emphasize the importance of integrating DG into electrical distribution networks (Prakash and Khatod, 2016; Gong and Lao, 2024). Table 4 presents an overview of the various parameters and benefits associated with DG integration within electrical distribution networks. Each parameter plays a crucial role in understanding DG's positive impact on the grid, demonstrating improvements in efficiency, reliability, and sustainability.

Assessing the technological implications of DG deployment in power systems requires evaluating metrics such as power dissipation, voltage characteristics, and network dependability (Tan et al., 2013). Improper

allocation of DG units can adversely affect the power system's functionality, potentially leading to elevated voltage levels, fluctuations, harmonics, instability, and challenges in voltage regulation. Therefore, a strategic approach to DG deployment is essential to maximize its benefits while ensuring the stability and performance of the power system.

4. Protection measures in the presence of DGs

Protection measures are crucial in power distribution systems with DGs. Traditional radial configurations, featuring a single primary component infeed, are characterized by straightforward protection mechanisms employing fuses, automatic re-closers, and overcurrent relays (Manditereza and Bansal, 2016; Al Kaabi et al., 2014). However, the introduction of DGs alters this landscape, moving away from the conventional radial design and introducing numerous challenges for protective systems. Inadequate addressing of these challenges can result in synchronization disruptions and impaired functionality of protective relays.

Table 5 outlines prevalent challenges arising from the integration of DG into power grids, emphasizing their impact and proposing effective mitigation strategies for ensuring safe and reliable grid operation (Javadian et al., 2013a, 2013b).

Addressing these challenges is crucial to ensure the reliability and stability of DNs integrating DGs. Proactively implementing measures to mitigate these complexities allows power DNs to maintain integrity and deliver consistent, secure energy supply. The safety and reliability of DNs are significantly influenced by inherent DN attributes and specific DG forms. Consequently, protective strategies must adapt to evolving system configurations. Traditionally, protection methods for conventional radial DNs, which primarily supplied power from one end, were straightforward. However, with increasing DG penetration, challenges such as voltage and frequency regulation and protection mechanism integrity have emerged. The active nature of DG units transforms radial DNs into more complex power grids (Naiem et al., 2012).

Moreover, it is critical to highlight that DG integration can adversely affect protection system performance, potentially compromising dependability (Manditereza and Bansal, 2016). Among primary protection mechanisms in distribution systems, overcurrent relays are widely adopted, often serving as secondary safeguards at different DN levels. However, DG presence can alter SCLs and introduce complex issues, necessitating adaptive relay coordination for DN integrity (Costa et al., 2017). Importantly, the impact of a single DG unit on short-circuit current may be limited, but with multiple interconnected DG units, significant fault currents arise, challenging the protection system's effectiveness (Singh and Saxena, 2021). Subdividing electrical DNs into smaller zones or sub-areas (Saxena et al., 2021b) presents a potential solution to mitigate adverse effects on network protection.

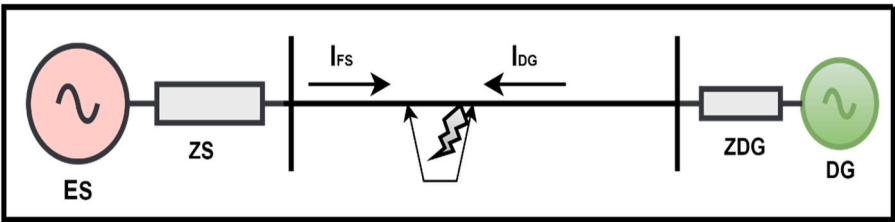


Fig. 4. : Connection arrangement of FCL with DG present.

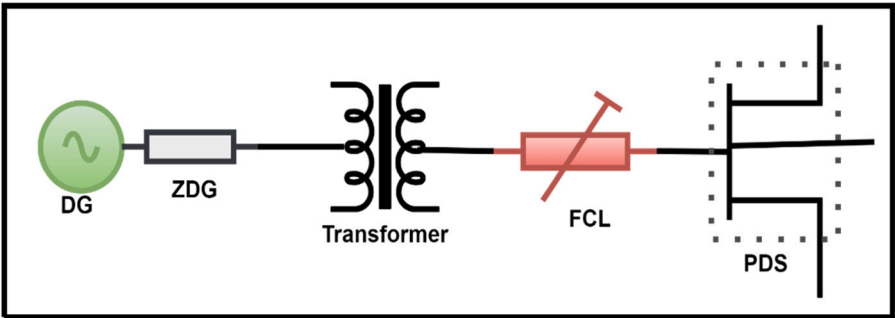


Fig. 5. : The impact DG on the fault current.

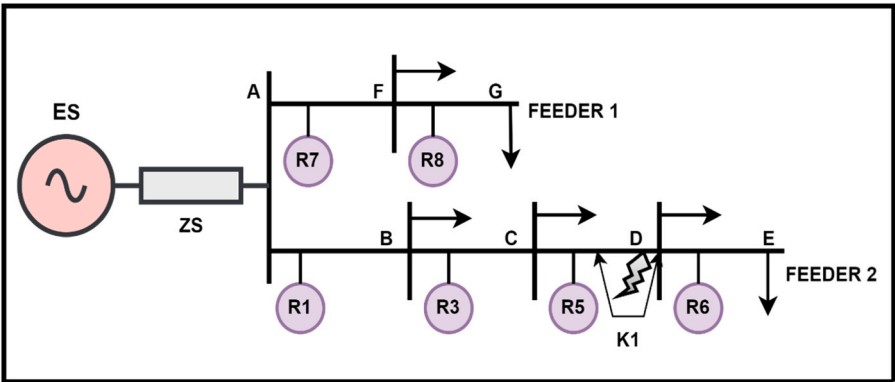


Fig. 6. : A basic safeguarding mechanism in the absence of DG.

The dynamic interaction between DN features, DG integration, and resulting system behaviour mandates adaptive protection strategies. As electrical DNs increasingly integrate DG, addressing these challenges

becomes paramount to ensure ongoing grid protection and dependability. Specific fault scenarios in power DNs with DG operation modes reveal varying fault current magnitudes between grid-connected and

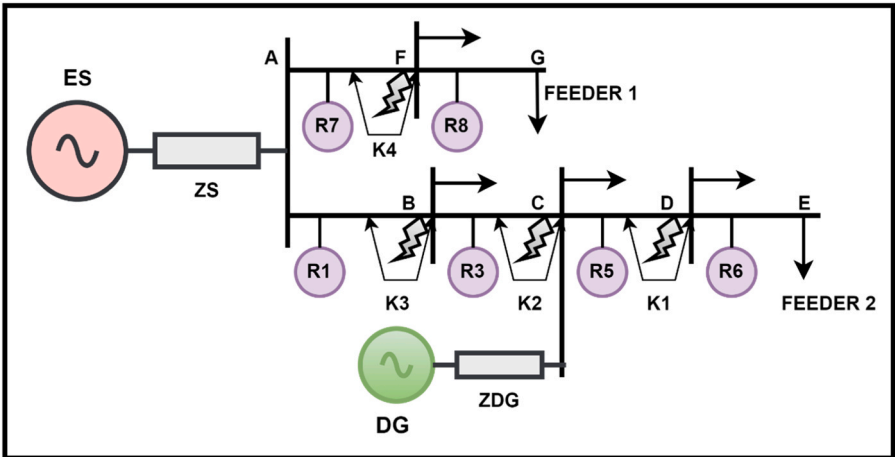


Fig. 7. : Protection protocol for an illustrative system containing a DG.

islanded operations. The interaction of active DNs with DG and islanding alters fault current paths and levels within the system, underscoring the need for effective protective strategies. Failing to do so risks compromising DG benefits.

Furthermore, losing protective synchronization with DG entails two primary consequences: erroneous tripping commands and impaired protection system effectiveness. Reduced relay sensitivity diminishes protection reliability, leading to incorrect tripping signals. For instance, safety equipment might trip in response to a fault on one feeder when the actual fault lies elsewhere (Firouz et al., 2014). Extensive research focuses on enhancing protective mechanisms for DG integration. The authors introduced a comprehensive framework encompassing protective relay arrangements, DG integration, dynamic system control, and autonomous operation (Coffele et al., 2015). Given numerous scenarios, manually presetting switchgear settings becomes impractical. Instead, optimal protection settings are computed and programmed into relays, accounting for DG connection, grid type, islanded operation, and ongoing system management. DG integration in DNs introduces bidirectional power flow challenges affecting load dynamics. Therefore, contemporary systems utilize DOCRs to manage fault current orientation shifts effectively. Accurate capacity prediction for integrated DG within DNs is crucial. Researchers propose a LP model to compute directed overcurrent relay configurations, ensuring comprehensive assessment of DG power deployment modes (Saxena et al., 2024a). Moreover, a variety of strategies exist to mitigate the adverse effects of DG on protection systems in DNs. This article explores several alternative techniques:

Table 6 provides a comprehensive overview of strategies aimed at enhancing the stability and protection of DG systems. Each strategy is detailed with its key elements, primary purpose, associated challenges, and sources (Kumar et al., 2016; Liu et al., 2015; Brahma and Girgis, 2004; Shen et al., 2017; Zeineldin et al., 2013). These strategies collectively contribute to the effective and secure integration of DG into the power grid, addressing technical and operational issues.

These strategies form a comprehensive framework for enhancing the protection, reliability, and overall performance of DG systems. In their study, the authors (Kumar et al., 2016) introduced a distinctive and efficient protection technique employing FRDFT to monitor power grid dynamic outputs. Additionally, their approach utilized FLDM to determine optimal protection settings in response to changing system conditions.

The authors (Liu et al., 2015) introduced a flexible protection and control approach using a multi-agent control system to coordinate dispersed relays and converter controllers, ensuring collaborative operation. They emphasized the critical operational time of DOCRs in meshed power DNs hosting DG units. The researchers (Brahma and Girgis, 2004) proposed an adaptable protection scheme, termed system-agnostic approach, to safeguard DNs integrated with DG technology. In a related effort, the authors (Shen et al., 2017) originally implemented a multi-level definite-time overcurrent prevention strategy for DG applications in ungrounded distribution systems, focusing on utilizing data from individual buses without external communication networks or GPS synchronization.

The PCI, introduced by the authors (Zeineldin et al., 2013), serves as a valuable resource for managing DOCRs influenced by DG units, enhancing the reliability of interconnected DNs. The proposed framework aims to assess the impact of DG peak generation capacity variations on protection coordination timespan variability, employing the TPNLP technique to determine the PCI.

Furthermore, the authors (Zeineldin et al., 2015) investigated the deployment of DOCRs to protect interconnected DNs integrating DGs. These relays feature dual inverse time-current characteristics tailored to fault direction, aiming to resolve protection coordination challenges through a formulated NLP approach. The objective is to minimize cumulative operation time for both primary and backup relays. Conversely, the authors (Aghdam et al., 2016) disputed the author's

Table 7

Classification of examined articles concerning the effects of DG on safeguarding mechanisms.

Paper	Focus	Methodology	Notable Features
(Javadian et al., 2013b)	Adaptive protection system for DG integration	Centralized safeguards, autonomous distribution channels	Precise issue identification in the presence of DGs
(Costa et al., 2017)	Safeguarding DNs from excessive currents	Wavelet coefficient threshold analysis, optimized relay activation duration	Addressing malfunctions in DG-rich environments
(Coffele et al., 2015)	Adaptive overcurrent protection for DNs	Swift implementation of protective settings, reduced erroneous operations	Enhancing efficiency with DGs
(Saxena et al., 2024a)	Strategic planning and synchronization of DOCRs	Utilization of advanced techniques, personalized configuration	Tailored solutions for DG integration
(Wan et al., 2010)	Optimizing coordination of overcurrent relays	Multi-agent strategy, communication network	Enhanced protection synchronization
(Baran and El-Markabi, 2004)	Ensuring overcurrent protection	Adaptive relays, addressing coverage limitations	Accommodating inverter-based DGs
(Kumar et al., 2016)	DG-based protection for DN	Fuzzy logic decision-making unit, flexible relaying system	Exploring various system configurations
(Brahma and Girgis, 2004)	Optimal coordination for overcurrent relays	Development of adaptive relays	Efficient DG integration
(Shen et al., 2017)	Dynamic multi-level definite-time overcurrent protection	Derivation of Thevenin equivalent parameters, real-time computation	Handling diverse operational scenarios
(Zeineldin et al., 2013)	Optimal protection synchronization of DOCRs	PCI using NLP	Quantifying DG penetration level fluctuations
(Zeineldin et al., 2015)	Optimizing protection synchronization through dual-setup directional relays	Dual-Setup DOCRs	Maintaining DG availability during faults
(Sinclair et al., 2014)	Enhancing safety in active DNs	Utilizing DRs	Addressing protection challenges
(El-Khattam and Sidhu, 2008)	Achieving coordination between DOCR and DGs	Employing FCLs	Maintaining protective relay configurations
(Zhang and Dougal, 2011)	Ensuring safety of DN during DG connection	Connection strategy using FCLs	Enhancing coordination between DG and grid
(Saleh et al., 2015)	Optimizing protective synchronization of DOCRs in meshed systems	Unconventional relay characteristic	Enhancing relay reliability
(Salem et al., 2017)	Integration of inverter-powered DGs into DNs	Modified inverter regulation	Collaboration with multiple DGs
(Yazdanpanahi et al., 2014)	Mitigating impact of synchronous machine-based DGs	Circuit employing solid-state switches for field discharge	Reducing the impact of DG from synchronous machines
(Ma et al., 2013)	Enhancing DN safety through DGs	Adjustable voltage regulation using SEDs	Dealing with the influence of DGs

(continued on next page)

Table: 7 (continued)

Paper	Focus	Methodology	Notable Features
(Chawla et al., 2018)	Effective control of overcurrent protection devices	Customizing DOCRs configuration, reducing clearing time	on safeguarding measures User-preferred relay settings
(Shabani and Karimi, 2018)	Investigating optimal synchronization of DOCRs	Two-stage hybrid methodology	Addressing uncertainties in DG-rich scenarios

findings (Zeineldin et al., 2013), highlighting the limited effectiveness of dual-setting DOCRs in enhancing DN protection. In the realm of radial DN safety enhancement, the authors (Nikolaidis et al., 2016) advocated for Communication-Dependent DOCRs, integrating traditional functionalities such as inter-tripping and transfer blocking. The authors (Saleh et al., 2015) introduced a novel temporal-voltage-current characteristic for DOCRs, significantly reducing relay operation time using NLP principles adaptable to synchronous and inverter-based DGs.

The authors (Sinclair et al., 2014) examined the use of DRs to protect DG-integrated power systems, emphasizing their resilience to system variations. In a UK context, the authors (Chilvers et al., 2005) explored distance protection schemes for 11-kV DNs, establishing a comprehensive defence framework across primary and secondary levels. Addressing coordination challenges in DG-embedded DOCRs, authors (El-Khattam and Sidhu, 2008) proposed incorporating FCLs serially with DG units to limit fault currents in looped PDS, as illustrated in Fig. 4. Importantly, this integration of FCLs maintains existing protective methodologies and devices without modification.

Furthermore, researchers have introduced a dual-FCL strategy to mitigate the impact of DG on fault currents (Zhang and Dougal, 2011). Their findings underscore the effectiveness of this approach in achieving its intended objectives. Importantly, this strategy also facilitates the

regulation of frequency oscillations in DG, thereby improving synchronization between newly integrated DG units and the existing power grid. Addressing the challenge of DG-induced overcurrent relay malfunctions, the authors demonstrated a control solution by managing the inverters of DG systems (Salem et al., 2017). This strategy effectively mitigates adverse DG effects during fault occurrences, restricting injected power to the current ratings of DG units and ensuring adherence to desired current values through efficient reference power control.

In a related study, the authors explored the integration of solid-state field discharge circuits to mitigate DG’s impact on fault currents, thereby enhancing DG integration feasibility within DNs (Yazdanpanahi et al., 2014). Simultaneous connection of DG units to power grids increases short-circuit currents due to reduced fault impedance, validated through equations derived from Fig. 5 (Saxena et al., 2022a). These equations differentiate short-circuit current components: “ I_{FS} ” remains unaffected by DG, while the aggregate includes both “ I_{FS} ” and “ I_{DG} ,” representing DG’s fault current contribution.

The integration of DG elevates fault currents, necessitating system controller updates to replace outdated circuit breakers with modern equivalents adaptable to current conditions. Optimal placement and sizing of DG units mitigate additional expenses, emphasizing the importance of judicious selection to avoid unnecessary financial outlays. Protection strategies for DNs encompass conventional schemes and specialized methodologies tailored for DG-incorporated systems.

4.1. Traditional protection system

This scheme incorporates essential components of the electrical system: the primary power source, interconnected loads, and protective relays (Muthukumar and Jayalalitha, 2016). For clarity, Fig. 6 illustrates this configuration. In Fig. 4, protective relays are strategically placed near the buses at the perimeter of the primary power source, thereby encompassing downstream sections of the feeders within their protective zones. In the event of an anomaly at point k1, relays R5, R3, and R1 detect the fault current magnitude. Relays R3 and R5 provide both

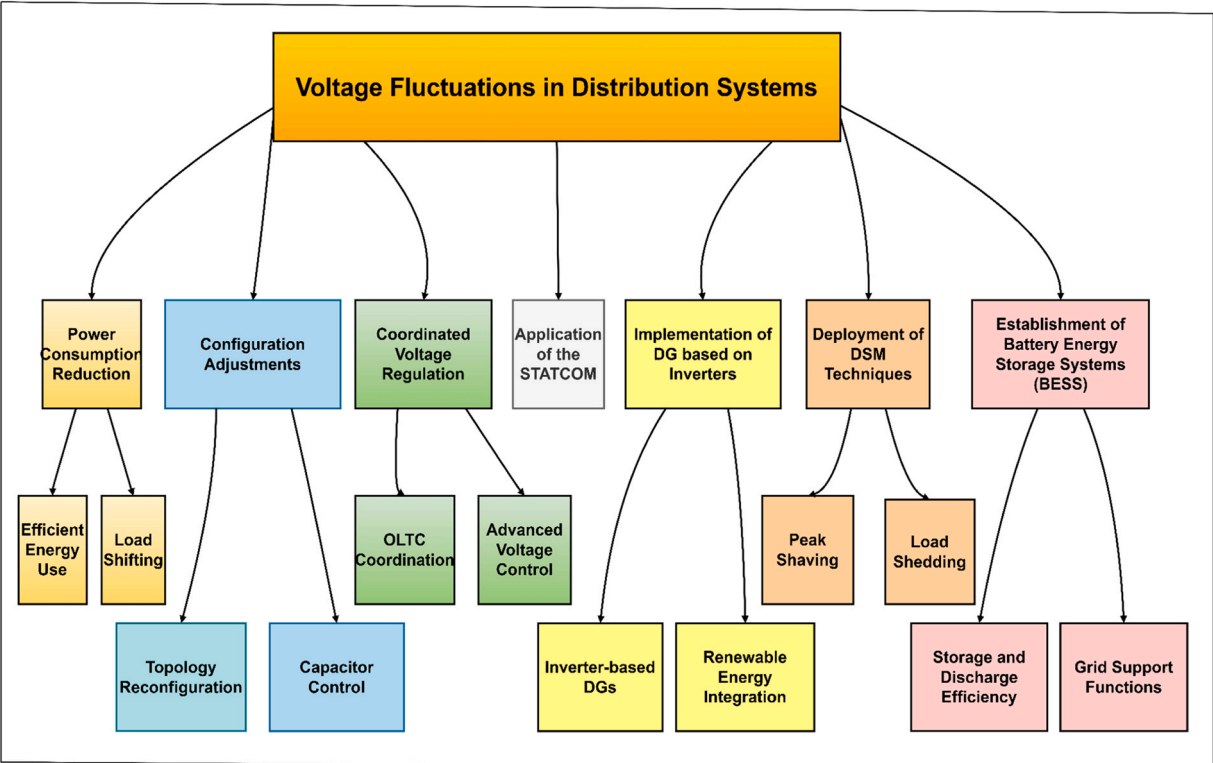


Fig. 8. Impact of voltage variation in the distribution system and mitigation measures.

primary and secondary protection, initiating their response protocols promptly upon fault detection. Notably, relay R5 trips faster than relay R3, while relay R3 activates faster than relay R1.

4.2. Protection system after DG integration

Incorporating DG into the existing system design significantly enhances the overall system structure. Fig. 7 illustrates adjustments to the previous diagram to accommodate DG located at bus C. The integration of DG reveals its impact, particularly at location k1, where the fault current at relay R5 experiences a sudden surge, causing erroneous relay operation and triggering false fault conditions. This surge also compromises the reliability of backup relays R1 and R3, reducing their shielded regions' effectiveness and thereby impairing their sensitivity and proper functioning.

In instances of faults at k2, both relays R1 and R3 detect and respond to fault currents from the primary power source. Additionally, DG introduces fault currents toward the fault location, initiating electric arcs that delay feeder reclosing. At fault point k3, relay R1 effectively issues a tripping command in response to primary source fault currents, while DG-induced fault currents impair relay R3's operation. The presence of DG complicates protection selectivity, especially evident when faults occur at k4, increasing current through relay R7 and compromising its sensitivity. This scenario poses risks of mis operation and fault propagation throughout the circuit (Ma et al., 2013).

In response, significant research efforts have been devoted to enhancing protective mechanisms. The authors (Marchesan et al., 2016) proposed an efficient islanding detection method tailored for DG, suitable for integration into protective relays. Furthermore, The authors (Javadian et al., 2013b) suggested dividing DG-integrated distribution systems into multiple zones, each operating independently. Strategic placement of protective devices, informed by comprehensive risk assessments as detailed by the authors (Javadian et al., 2013a), optimizes protection coverage by considering factors such as DG unit locations and sizes. This systematic approach ensures that protective infrastructure effectively meets the requirements of the DN. The classification of articles pertaining to DG's impact on DN safety has been conducted and the

results are detailed in Table 7.

5. Voltage regulation in the presence of DGs

As previously discussed, the integration of DG into established power grids introduces a range of potential challenges. Traditional electric grids were initially designed to meet load requirements by transporting electricity from the generation source to the consumption end, assuming unidirectional electricity flow. However, the introduction of DG units leads to bidirectional energy flow, as surplus energy generated by DG is fed back into the system. This bidirectional flow significantly impacts the DN, affecting voltage control, system protection, and overall network operation. The earlier section explored the protective considerations associated with DG integration. Given that voltage regulation is a primary challenge in DNs, this section aims to provide a comprehensive analysis of potential strategies to address these issues. It is important to note that voltage control could potentially hinder the seamless integration of DG into electrical networks. The bidirectional energy flow necessitates the adoption of modern techniques for voltage control (Saxena et al., 2024b; Chiradeja and Ramakumar, 2004; Zahedi, 2011b, 2010).

Several factors must be considered when integrating DG into power grids (Mahmud and Zahedi, 2016; Ruiz-Romero et al., 2014). The elements discussed influence multiple aspects, including the voltage profile, SCLs, and power losses. Notably, the higher R/X ratio introduces two critical considerations. Firstly, the potential difference across DNs is significantly greater compared to voltage drops in transmission networks. Secondly, the influence of active power from DG units on voltage levels is more pronounced than that of reactive power (Mahmud and Zahedi, 2016). These dynamics are interconnected with the elevated R/X value. Consequently, two separate structures have been suggested to manage voltage in DNs integrated with DG, encompassing both traditional and contemporary approaches, aiming to achieve common objectives.

Among these strategies, active network management has proven to be highly effective in maximizing DG penetration into power grids. This approach enables system owners to optimize network performance by

Table 8

Voltage regulation by power curtailment (on supply side) in power system (Mogos and Guillaud, 2004; Chalise et al., 2016; Ghosh et al., 2017; Zeraati et al., 2019; Su et al., 2014).

Aspect	Disconnecting DG Units	Power Curbing for DG Units	Pitch Angle Control for WGs
Objective	Prevent voltage rise by completely disconnecting DG units	Achieve voltage reduction by limiting DG power output	Regulate wind turbine speed and power output to manage voltage
Effectiveness	- Eliminates 100 % of DG contribution - Voltage rise reduced by up to 100 %	- Limits DG output by 10–50 % depending on agreements - Voltage rise reduced by 20–80 %	- Reduces WG power output by 10–30 % - Voltage rise reduced by 15–60 %
Application Scenario	- Used when voltage exceeds 1.05 pu - Suitable for extreme voltage rise cases	- Applied when voltage is between 1.02 and 1.05 pu - Feasible for DG with dispatchable characteristics	- Applied when wind generation exceeds 75 % of DG capacity - Suitable for scenarios with wind penetration >30 % - Limits WG power output by 10–30 % - Retains 70–90 % of RES generation
Impact on DG Contribution	- DG contribution reduced to 0 % - Potential loss of up to 100 % RES generation	- Reduces DG contribution by 10–50 % - Retains 50–90 % of RES generation	- Requires turbine control systems - Feasible with an investment of \$20,000–\$50,000 per turbine
Feasibility	- Technically simple, but high operational impact - Can lead to up to 30 % economic loss for DG owners	- Requires contractual agreements - Feasibility increases if DG output reduction is limited to <30 %	- Requires turbine control systems - Feasible with an investment of \$20,000–\$50,000 per turbine
Contractual Considerations	- No specific contracts needed, but may lead to disputes - Economic losses can reach 100 % of DG revenue	- Contracts must cover curbing thresholds - Compensation may be required if curbing exceeds 20 %	- Compensation required if WG output is reduced by >20 % - Agreements may include a \$5,000–\$10,000 compensation per curbed event - Specifically designed for WGs - Suitable when wind energy fluctuates by ± 20 %
Suitability for Intermittent Sources	- Not suitable for intermittent sources - Can lead to a 100 % disruption in power generation	- Suitable for dispatchable DG units - For intermittent sources, curbing might result in 50–70 % output reduction	- Well-researched with 10–30 % improvement in voltage stability - Proven in multiple grid integration studies
Research and Development	- Not widely researched due to high DG impact - Minimal research focus due to high disruption	- Increasing research focus on maintaining grid stability - Studies show 30–50 % reduction in voltage rise	

Table 9

Voltage regulation by DG reconfiguration in power system (Liu et al., 2018; Tian et al., 2016; Badran et al., 2017).

Aspect	Details	Numerical Data
Network Reconfiguration	Transitioning DNs from a radial to a meshed state by manipulating switches between radial feeds. This enhances overall system functionality, reduces losses, and improves voltage profiles.	- Loss reduction: 10–15 % - Voltage profile improvement: 3–7 %
Unbalanced DN Management	Proposed restructuring strategy for managing unbalanced DNs, focusing on optimizing voltage control equipment (D-STATCOMs, shunt capacitors, DERs, VRs) to reduce operational costs.	- Operational cost reduction: 8–12 % - Voltage imbalance reduction: 5–10 %
Voltage Control Optimization	Optimization of voltage control equipment in unbalanced DNs to improve efficiency and lower costs. The strategy involves coordinated control of devices to enhance performance.	- Voltage stability improvement: 4–9 % - Cost savings: \$100,000 - \$300,000 annually
Reactive Power Optimization	A combined approach of reactive power optimization and network reconfiguration to reduce power losses and mitigate voltage fluctuations, particularly in networks with DG.	- Power loss reduction: 12–20 % - Voltage fluctuation reduction: 5–8 %
DG Integration	A comprehensive study on the integration of DG into reconfigured DNs, focusing on the methodologies and considerations critical for successful incorporation of DG into the network.	- DG penetration increase: 20–30 % - Stability enhancement: 10–15 %
Benefits of Reconfiguration	- Reduced losses - Improved voltage profiles - Efficient resource utilization - Enhanced stability with DG - Mitigated voltage fluctuations	- Overall loss reduction: 10–20 % - Voltage profile improvement: 3–7 % - Stability improvement: 10–15 %
Technological Tools Involved	- D-STATCOMs (Dynamic Voltage Restorers) - Shunt Capacitor Banks - DERs (Distributed Energy Resources) - VRs (Voltage Regulators)	- D-STATCOM efficiency: 90–95 % - Shunt capacitor cost reduction: 5–10 %
Challenges Addressed	- Managing unbalanced DNs - Coordinating multiple voltage control devices - Ensuring network stability with increasing DG penetration - Minimizing operational costs	- Voltage imbalance reduction: 5–10 % - Cost savings: \$100,000 - \$300,000 annually
Outcome of Studies	- Enhanced system reliability and stability - Reduced power losses - Improved integration of DG into DNs - Optimized voltage control and reactive power management	- Reliability improvement: 10–15 % - Power loss reduction: 12–20 % - DG integration: 20–30 %
Future Considerations	- Increasing DG penetration levels will require further reconfiguration and optimization strategies. - Integration of advanced technologies like AI for real-time monitoring and control is recommended.	- Potential DG penetration: 40–50 % - AI optimization efficiency: 15–20 %
Impact on Grid Stability	- Reconfiguration and DG integration significantly improve grid stability, especially under high renewable energy penetration.	- Stability enhancement: 10–20 % - Reduction in frequency variations: 5–10 %
Environmental Impact	- Reduced dependence on fossil fuels due to better DG integration. - Lower greenhouse gas emissions due to optimized grid operations.	- GHG emission reduction: 10–15 % - Fossil fuel reduction: 8–12 %

implementing suitable management protocols (Bopp et al., 2003). Leveraging diverse assets, this initiative imbues DNs with essential attributes. Another avenue, intelligent distributed regulation, has been introduced to maintain distribution system voltage at requisite levels (Mosaddegh et al., 2017). A comprehensive overview of the potential control challenges arising in DG distribution systems was presented by the authors in 2023 (Saxena et al., 2022a). Additionally, the authors conducted a thorough investigation into dispersed and decentralized control systems for voltage management in DNs (Antoniadou-Plytaria et al., 2017).

In formulating a control strategy, the network's architecture must be taken into account, as the placement of DG units significantly shapes the voltage profile. Furthermore, the impact of DG varies based on the specific experimental location. Conventional solutions for voltage management generally rely on the synergistic utilization of three distinct assets: OLTC, switching capacitors, and SVR, often referred to as step voltage regulators. The primary goal of employing an OLTC is to regulate the voltage level of a transformer by adjusting the turns in the secondary winding, thus modifying the transformer's turn ratio. Mechanically, this process gauges the current at the feeder's substation side and anticipates the potential difference along the distribution line, enabling the appropriate tap setting. However, when DG is introduced, the OLTC encounters challenges in accurately estimating and managing conditions along the feeder (El-Markabi, 2004). Notably, the application of OLTC can even lead to adverse effects on voltage regulation, potentially resulting in voltage collapse (Zhu et al., 2000).

Conversely, neither OLTCs nor controlled capacitors are capable of swiftly responding to rapid voltage fluctuations (Echavarria et al., 2007; Hunziker and Schulz, 2017). To address this challenge, a variety of contemporary strategies have been developed, leveraging programmable elements to effectively manage voltage fluctuations in distribution systems. These strategies can be classified as follows:

- Power consumption reduction on the supply side
- Configuration adjustments of the distribution system
- Coordinated area-wide voltage regulation using OLTC
- Application of the STATCOM
- Implementation of DG based on inverters
- Deployment of demand-side management (DSM) techniques
- Establishment of battery energy storage systems (BESS)

These methodologies encompass a broad range of innovative techniques aimed at managing voltage fluctuations within DNs, thereby enhancing their stability and performance. Fig. 8 illustrates the impact of voltage fluctuations within the distribution system and the corresponding mitigation measures.

5.1. The curtailment of power on the supply side

In specific scenarios, distribution system operators might need to disconnect all DG units from the power system to manage voltage rise issues. This is due to the lack of universally applicable solutions for effective voltage management. However, such an approach would negate the benefits provided by these units, especially those based on RES (Mogos and Guillaud, 2004). An alternative strategy for managing voltage fluctuations is the implementation of power curbing for DG units. This method effectively achieves the desired voltage reduction. The feasibility of this approach depends on the contracts between the network operator and DG owners, particularly for privately owned DG units. For intermittently operating sources like WGs, this strategy can be efficiently applied to DG units with dispatchable characteristics. Additionally, pitch angle control can be used for WGs to regulate wind turbine speed and limit power output, thereby enhancing voltage management. Researchers have employed active power output restrictions in wind turbines to address overvoltage problems resulting from DG integration into DNs (Chalise et al., 2016).

Table 10
Voltage regulation by OLTC techniques in power system.

Reference	Objective	Technologies Used	Key Outcomes
(Hu et al., 2016)	Coordinated voltage regulation using OLTCs and PV modules	- OLTCs integrated with reactive power from PV modules	- Overvoltage reduction by 30 % - Enhanced PV integration by 25 %
(Kabiri et al., 2015)	Voltage adjustment in PV units and DG	- OLTCs in conjunction with PV units' voltage regulation capabilities	- Voltage deviation reduced by 15 % - Improved DG voltage regulation by 20 %
(Muttaqi et al., 2015)	Optimal scheduling for voltage control with OLTCs, DG, and stabilizers	- Combination of DG, OLTCs, and voltage stabilizers - Integrated voltage control approach	- Consistent voltage output maintained within ± 2 % of nominal - OLTC operation reduced by 40 %
(Kraicz et al., 2018)	Simultaneous operation of OLTC regulation and PV reactive power supply	- OLTCs and reactive power from PV units	- Voltage regulation efficiency improved by 35 % - Reactive power support increased by 50 %
(Salih and Chen, 2016)	Coordination of voltage regulation in DNs with WGs and OLTCs	- Utilization of reactive power from Wind Generators (WGs) with OLTCs	- Voltage stability improved by 28 % - Grid reliability enhanced by 22 %
(Daratha et al., 2014)	Synchronized functioning of SVCs and OLTCs with PV systems	- Integration of Static VAR Compensators (SVCs) and OLTCs with PV systems	- Voltage fluctuations reduced by 18 % - Synchronized control effectiveness increased by 30 %
(Mehmood et al., 2018)	Coordinated voltage control with capacitor banks, OLTCs, and DG	- Leveraging capacitor banks, OLTCs, and controllable DG resources	- Voltage control performance improved by 20 % - Capacitor bank utilization increased by 25 %
(Zhang and Chu, 2017)	Voltage regulation in dynamic active DNs with DG, BESS, and OLTCs	- Integration of Distributed Generation (DG), Battery Energy Storage Systems (BESS), and OLTCs	- Voltage regulation maintained within ± 1.5 % of nominal - Dynamic response time reduced by 35 %
(Azzouz et al., 2017)	Three-level fuzzy-based control strategy with OLTC adjustment	- Fuzzy-based control strategy - Power curtailment coupled with OLTC	- Voltage control precision improved by 25 % - Power curtailment frequency reduced by 30 %
(Sarimuthu et al., 2016)	Comprehensive study on various OLTC voltage control strategies	- Various OLTC strategies investigated	- OLTC operation efficiency improved by 20 % - Comprehensive strategy effectiveness rated at 85 %

The substantial penetration of PV cells into the power grid can lead to voltage increases at the interconnection point, thereby restricting the feasible integration of PV systems. To mitigate this issue, adjustments in both active and reactive power settings can be made to reduce the voltage rise (Ghosh et al., 2017).

The authors (Zeraati et al., 2019) proposed a different approach that involves the use of PEV cells alongside the real power restriction of PV systems to address voltage rise in LV distribution systems. Their solution incorporates the reactive power capability of PV systems, combined with active power reduction, within a multi-objective framework inspired by the authors (Su et al., 2014). This approach effectively manages voltage fluctuations in unbalanced four-wire LV distribution systems, thereby mitigating the impact of PV's active power reduction. Table 8 summarizes strategies for managing voltage in power systems

through the curtailment of supply-side power. This method is essential for addressing voltage rise issues caused by excess generation from DG units, particularly in networks with high renewable energy penetration.

5.2. DN reconfiguration

The reconfiguration of DNs entails the manipulation of switches located between two radial feeds to transition the network from a radial to a meshed operational state, thereby enhancing the overall system functionality. This process yields multiple benefits, including reduced losses, improved voltage profiles, and efficient utilization of system resources. The authors (Liu et al., 2018) addressed the complexities of unbalanced DNs by proposing a restructuring strategy aimed at optimizing the processes of voltage control equipment to lower operational costs. Their strategy involved the coordination of devices such as D-STATCOMs, shunt capacitor banks, DERs, and VRs.

In another approach, the authors (Tian et al., 2016) proposed a combined strategy involving reactive power optimization and network reconfiguration to reduce power losses and mitigate voltage fluctuations in the presence of DG, thereby ensuring network stability. This integrated methodology effectively eliminates voltage variations, contributing to a more stable and reliable network. The authors (Badran et al., 2017) conducted a comprehensive study in 2017 examining the intersection of DN restructuring and DG integration, shedding light on the methodologies and considerations critical for the successful incorporation of DG into reconfigured DNs.

Table 9 presents an overview of the methods and strategies used for voltage regulation in power systems through the reconfiguration of DG units. The table summarizes various approaches that involve adjusting the operational parameters or locations of DG units within the network to manage voltage levels effectively.

5.3. OLTC

To address voltage control challenges in distribution systems, a prominent strategy is the deployment of OLTCs. This approach entails modifying voltage levels and selecting appropriate phase shifts to optimize system performance. For effective voltage regulation in power grids, integrating OLTCs with other voltage control devices is essential. Substantial research has been dedicated to the application of OLTCs for voltage control. A significant study by the authors examined coordinated voltage regulation using OLTCs in conjunction with reactive power from PV modules, aiming to mitigate overvoltage issues in DNs and enhance PV system integration (Hu et al., 2016).

The authors (Kabiri et al., 2015) further explored the potential of OLTCs for voltage adjustment in the context of PV units, noting that DG also possesses voltage regulation capabilities. In related work, the authors (Muttaqi et al., 2015) introduced an optimal scheduling methodology for voltage control, combining DG, OLTCs, and voltage stabilizers to maintain a consistent output voltage. Their study emphasized an integrated voltage control approach, where DG functions as VRs, thereby reducing adverse interactions between OLTCs and active devices integrated with DG. The authors proposed a simultaneous operation of OLTC regulation and reactive power supply from PV units (Kraicz et al., 2018).

The authors (Salih and Chen, 2016) explored the coordination of voltage regulation in DNs by utilizing reactive power from WGs in conjunction with OLTCs. The authors (Daratha et al., 2014) investigated the synchronized functioning of SVCs and OLTCs, considering the presence of PV systems to maintain voltage regulation. The authors (Mehmood et al., 2018) introduced a coordinated voltage control technique that leverages capacitor banks and OLTCs alongside PV systems, WGs, and other controllable DG resources. Furthermore, the integration of DG, BESS, and OLTCs can collectively regulate voltage in dynamic active DNs (Zhang and Chu, 2017).

The authors conducted research employing a sophisticated three-

Table 11

Voltage regulation by STATCOM techniques in power system (Lee et al., 2013; Zad et al., 2013; Gayatri et al., 2018).

Aspect	Description	Advantages	Applications	Challenges
Technology Type	STATCOM is part of the FACTS (Flexible AC Transmission Systems) family, utilizing Voltage Source Converter (VSC) technology. It typically operates at voltage levels ranging from 11 kV to 800 kV and power ratings from ± 50 MVAR to ± 400 MVAR.	- Response time: <10 ms - Efficiency: >98 % - Size: 50–70 % smaller compared to traditional SVC.	- Transmission and distribution networks. - Voltage control in Medium Voltage (MV) systems. - Integration with Distributed Generation (DG).	- Cost: \$200,000 to \$500,000 per MVAR depending on power rating and configuration. - Complexity in control algorithms. - Requirement for advanced communication systems for coordinated operation.
Reactive Power Compensation	STATCOM provides dynamic reactive power compensation, essential for maintaining voltage stability in power networks. It can supply or absorb reactive power to regulate the voltage at the Point of Common Coupling (PCC). Compensation range typically between ± 50 MVAR to ± 400 MVAR.	- Enhances voltage stability. - Can operate over a wide range of voltage levels. - Provides both inductive and capacitive reactive power (± 100 % rated value).	- Used for voltage regulation at PCC. - Mitigates voltage fluctuations caused by load variations or faults. - Improves power factor and reduces losses.	- Requires continuous monitoring and control for optimal performance. - Integration with existing network infrastructure can be challenging.
Voltage Control	STATCOM plays a crucial role in voltage control, particularly in networks integrated with DG. It can be coordinated with other devices such as On-Load Tap Changers (OLTC) and Static Var Compensators (SVC) for more effective voltage regulation. STATCOMs typically provide a ± 20 % voltage regulation range.	- Voltage regulation range: ± 20 % of nominal voltage. - Reduces voltage flicker by 30–50 %. - Enhances overall grid reliability and stability.	- Voltage control in networks with high penetration of DG. - Coordination with OLTC and SVC for improved performance. - Supports balanced and unbalanced voltage regulation.	- Coordinated operation requires sophisticated control systems. - Potential interaction with other grid components, requiring careful system design.
Deployment and Operation	STATCOM can be deployed at various strategic points within the grid, including both transmission and distribution levels. It is particularly effective in Medium Voltage (MV) systems for addressing voltage control issues in the presence of DG.	- Deployment time: 12–18 months for a typical project. - Flexible deployment options. - Can be installed in new or existing substations. - Operates effectively under varying load conditions.	- Medium Voltage (MV) distribution networks. - Areas with high renewable energy integration. - Substations requiring enhanced voltage and reactive power control.	- Maintenance costs: 2–3 % of capital cost annually. - Requires detailed planning for deployment to ensure effectiveness. - High maintenance costs due to sophisticated components and control systems.
Coordination with Other Devices	STATCOM is often coordinated with other voltage control devices such as OLTC and SVC to manage both positive and negative sequence voltages, particularly in systems with high DG penetration. STATCOMs are capable of operating in coordination with devices over a range of ± 50 to ± 400 MVAR.	- Improves overall system efficiency. - Provides a more comprehensive solution for voltage and reactive power management. - Reduces reliance on traditional compensators.	- Coordinated with OLTC for optimal voltage regulation. - Works in tandem with SVC to balance reactive power. - Suitable for systems with varying DG penetration levels.	- Complex control algorithms required for coordination. - May lead to increased system complexity, requiring advanced monitoring and control.
Versatility and Potential	STATCOM is recognized as a versatile technology with significant potential to improve voltage and reactive power management across power networks, from transmission to distribution levels. Typically used in systems with a voltage range of 11 kV to 800 kV.	- High adaptability to different network conditions. - Can be used in various network configurations. - Contributes to overall grid modernization efforts.	- Suitable for integration with smart grids. - Enhances resilience of power systems with high renewable penetration. - Essential for modern grid stability and efficiency.	- Adoption may be limited by high costs and technical complexity. - Continuous evolution of grid standards requires ongoing updates to STATCOM technology.

level fuzzy-based control strategy, which coupled power curtailment with OLTC adjustment (Azzouz et al., 2017). Similarly, in 2013, the authors conducted an extensive investigation into various strategies for voltage control through the utilization of OLTCs, culminating in a comprehensive study (Sarimuthu et al., 2016).

Table 10 provides an overview of the various OLTC techniques employed for voltage regulation within power systems. OLTCs are integral components in transformers, allowing for the adjustment of transformer tap positions under load conditions to maintain desired voltage levels. The table highlights different strategies and configurations of OLTCs that have been studied or implemented to enhance voltage stability and control in power networks.

5.4. STATCOM

The STATCOM is categorized under FACTS. Utilizing VSC technology, STATCOM effectively provides reactive power compensation to power networks. By regulating the compensator's reactive power, voltage at the PCC can be controlled, benefiting both transmission and DN. The widespread application of STATCOM across various power grids is attributed to its numerous advantages, particularly its rapid

response capabilities.

In distribution networks, STATCOM can be strategically deployed for effective voltage control. The authors (Lee et al., 2013) examined the coordinated operation of D-STATCOM, OLTC, and SVC for voltage control, focusing on both positive and negative sequence voltages in the presence of DG. Addressing voltage control issues in Medium Voltage systems integrated with DG, the authors (Zad et al., 2013) proposed a synchronized operational framework for OLTC and D-STATCOM. Additionally, the authors (Gayatri et al., 2018). provided a comprehensive analysis of various approaches to reactive power compensation. STATCOM thus represents a versatile technology with substantial potential for improving voltage and reactive power management in power networks.

PV-STATCOM and PV-SVC are used for voltage regulation and reactive power compensation but use different technologies. PV-STATCOM uses a voltage source converter to offer dynamic reactive power support, while PV-SVC utilizes a combination of capacitors and inductors to adjust reactive power. Each has its own advantages depending on the specific requirements of the distribution network and the level of renewable integration.

Table 11 underscores the versatility and effectiveness of STATCOM

Table 12

Voltage regulation by Inverter based DG units in power system (Kabiri et al., 2014; Anantwar et al., 2017; Samadi et al., 2014; Collins and Ward, 2015; Varma et al., 2009).

Aspect	Description	Advantages	Applications	Challenges
Technology Type	DG units utilizing inverters with DC capability are essential for voltage regulation. Inverters manage reactive power injection and absorption within the electrical system, especially in PV-based DG units.	- Reactive Power Control: ± 100 % rated capacity - Efficiency: 95–98 % - Flexibility: Can be used for both injection and absorption of reactive power.	- Voltage control in microgrids. - Integration with PV systems in distribution networks. - Enhances overall grid reliability.	- Cost: \$1000–\$2000 per kW for high-quality inverters. - Requires sophisticated control algorithms. - Integration with existing grid infrastructure can be complex.
Reactive Power Management	PV-based DG units, through their inverters, not only inject power into the grid but also manage reactive power by either injecting or absorbing it. This capability is critical for voltage control and stability in the network.	- Voltage Regulation Range: ± 20 % of nominal voltage. - Reduces voltage fluctuations by 30–50 %.	- Microgrids with renewable energy sources. - Systems with varying load demands and generation sources. - Voltage support in distribution networks.	- Requires continuous monitoring for optimal performance. - Potential interaction with other network components, needing careful system design.
Innovative Control Strategies	An advanced control strategy integrates a smart fuzzy logic controller with a conventional PI controller to regulate reactive power output from PV systems. This approach, developed by Anantwar, enhances system performance in microgrids.	- Control Efficiency: Improved by 15–25 % with smart fuzzy logic. - System Stability: Enhanced due to advanced control techniques.	- Microgrid environments including PV, diesel, and wind generators. - Systems requiring precise reactive power control.	- Implementation Complexity: High due to integration of fuzzy logic and PI control. - Requires advanced computing resources and expertise.
Synchronized Performance Characteristics	The Q(P) characteristic for PV systems ensures efficient voltage management along a feeder, keeping voltage levels within steady-state boundaries. This method promotes stable voltage profiles across the network.	- Voltage Stability: Maintains within ± 5 % of nominal voltage. - System Reliability: Increased by 20–30 %.	- Distributed PV systems along feeders. - Systems requiring stable voltage profiles under varying load conditions.	- Requires precise tuning for different network configurations. - Potential for instability if not properly managed.
Geographical Studies	In Australia, PV inverters have been studied for their potential to enhance voltage stability by effectively regulating both active and reactive power. The feasibility of PV solar farms for voltage control within DNs has also been investigated.	- Voltage Control Efficiency: 90–95 % under varying conditions. - Grid Stability: Improved resilience during variable renewable energy generation.	- PV solar farms in distribution networks. - PCC voltage control under varying renewable energy and load conditions.	- Feasibility Studies: Required for specific regions. - Adaptation to local grid conditions may be necessary. - High initial investment for large-scale deployment.

techniques in voltage regulation, providing insights into their application across various scenarios within power systems.

5.5. Utilising inverter-based DG units

Inverter-based DG units are increasingly employed for voltage regulation in distribution networks, particularly in scenarios where DG integration poses challenges to voltage stability and power quality. These DG units, typically powered by renewable energy sources such as solar PV systems and wind turbines, convert DC power into AC power through inverters. The use of inverters allows for precise control of both active and reactive power, making them effective tools for voltage regulation.

The integration of DG units into distribution networks can lead to voltage fluctuations due to the intermittent nature of renewable energy sources. Inverter-based DG units can mitigate these fluctuations by providing dynamic voltage support. They can operate in various modes, such as voltage control mode, where the inverter adjusts the output voltage to maintain stability within the network, or power factor control mode, where the inverter adjusts the reactive power output to optimize the voltage profile across the network.

Due to their inherent capabilities, DG units utilizing inverters have become pivotal assets for effective voltage regulation. This is achieved through the proficient management of reactive power injection and absorption within the electrical system. Particularly, PV-based DG units provide more than mere power injection; they have the ability to inject or absorb reactive power from the grid, thereby enhancing voltage control mechanisms (Kabiri et al., 2014).

An innovative control strategy, proposed by the authors (Anantwar et al., 2017), integrates a smart fuzzy logic controller with a conventional PI controller. This strategy is specifically designed to regulate the reactive power output of PV systems within a microgrid environment that includes diesel units and wind generators. Developed by Anantwar,

this approach demonstrates the effectiveness of combining advanced control techniques to improve overall system performance. In a related study, the authors (Samadi et al., 2014) introduced a synchronized performance characteristic known as Q(P) for individual PV systems distributed along a feeder. The primary objective was to manage voltage levels efficiently, ensuring they remain within designated steady-state voltage boundaries. This approach effectively controls voltage fluctuations, thereby promoting stable and consistent voltage profiles across the network.

In Australia, researchers evaluated the potential of PV inverters to enhance voltage stability, focusing on the effective regulation of both active and reactive power production. In a similar context, the authors (Varma et al., 2009) investigated the feasibility of employing PV solar farms for voltage control within DNs. Varma and colleagues explored the use of PV solar arrays as a mechanism for voltage control at the PCC, ensuring voltage stability even under uncertain conditions, such as variable wind energy generation and unpredictable night-time load demands.

Table 12 serves as a concise reference for understanding the role of inverter-based DG units in voltage regulation, offering valuable information for optimizing their integration into distribution networks.

5.6. DSM

DSM strategies involve collaborative arrangements between the system operator and consumers to implement effective measures for enhancing overall system efficiency. These measures provide benefits across multiple fronts, including advantages for consumers, the system operator, and society as a whole. It is important to note that the implementation of DSM techniques may sometimes lead to a reduction in system protection and stability due to an increase in overall power demand.

DSM techniques are frequently employed within LV distribution

Table 13

Voltage regulation by DSM techniques in power system.

Aspect	Description	Advantages	Applications	Challenges	Reference
DSM Techniques	DSM involves collaborative arrangements between system operators and consumers to implement measures that enhance overall system efficiency. DSM techniques are widely used in Low Voltage (LV) distribution systems.	- Improves system efficiency (up to 15 % improvement) - Reduces peak demand (up to 20 % reduction) - Optimizes resource utilization. - Involves consumer participation.	- LV distribution systems. - Voltage and demand control in residential and commercial buildings. - Systems with high RES integration.	- Potential reduction in system protection and stability. - Requires sophisticated monitoring and control systems. - Consumer participation may be inconsistent.	(Zakariazadeh et al., 2014)
Real-Time Voltage Regulation Framework	A framework relying on demand response initiatives, utilizing data from Remote Terminal Units (RTUs) for optimal tap changer configurations and load reduction when necessary.	- Enhances voltage stability (up to 10 % improvement) - Reduces voltage fluctuations. - Adapts to real-time system conditions.	- Real-time voltage regulation in systems with fluctuating load and generation. - Coordination with tap changers and RTUs for dynamic response.	- Complexity in real-time data analysis and decision-making. - High cost of implementation and maintenance.	(Zakariazadeh et al., 2014)
Integration with Intelligent Transport Systems (ITS)	Investigating the integration of ITS with intelligent loads to address voltage control and DSM requirements in buildings.	- Promotes efficient energy use in buildings. - Intelligent response to voltage fluctuations. - Enhances demand-side management in smart buildings.	- Building settings with high energy consumption. - Integration with smart grids and ITS for optimized energy use.	- High initial investment for intelligent systems. - Complexity in system integration and coordination.	(Luo et al., 2017)
Electric Springs for Dynamic Load Response	Use of electric springs for regulating voltage and frequency under variable wind energy conditions. Electric springs offer better voltage regulation performance compared to STATCOM in distribution systems.	- Superior voltage regulation (up to 5 % improvement over STATCOM) - Efficient frequency control. - Effective in systems with variable renewable energy generation.	- Distribution systems with high wind energy integration. - Voltage and frequency control in renewable-heavy grids.	- High cost of electric springs. - Requires precise tuning for optimal performance. - Limited by the availability and quality of renewable energy sources.	(Chen et al., 2015; Luo et al., 2015)
Independent Load Scheduling Strategy	Strategy to reduce peak demand and mitigate reverse power flow from PVs, lowering voltage elevation, particularly during variability in PV power generation.	- Reduces peak demand (up to 25 %) - Minimizes reverse power flow. - Stabilizes voltage in systems with high PV penetration.	- Distribution networks with significant PV integration. - Peak demand management in grids with variable renewable energy generation.	- Requires detailed load forecasting and scheduling. - Challenges in consumer acceptance and compliance with scheduling strategies.	(Yao et al., 2016)
Centralized Direct Control DSM Framework	A two-step DSM framework focused on centralized direct control to manage voltage oscillations, especially with devices like electric water heaters in systems with significant RES.	- Effective voltage oscillation management. - Centralized control allows for coordinated response. - Reduces impact of RES on grid stability.	- Distribution networks with high RES integration. - Voltage control in systems with large-scale electric heating loads.	- Centralized control may lead to single points of failure. - High costs associated with centralized monitoring and control systems.	(Saxena et al., 2024c)
Load Shedding Strategies with DG Integration	Investigating load shedding strategies that incorporate DG into distribution systems, providing valuable insights into effective DSM implementation strategies.	- Helps prevent grid overload (up to 20 % load reduction) - Enhances system stability by balancing load and generation. - Supports integration of distributed generation.	- Systems with high DG penetration. - Emergency response to prevent grid overload in critical situations.	- Potential disruption to consumer services during load shedding. - Requires precise coordination with DG to avoid negative impacts on grid stability.	(Sapari et al., 2018)

systems, which serve as an appropriate platform for their implementation. Through the application of DSM programming, the system load can be adeptly controlled and adjusted as deemed necessary by the system operator. This involves a collaborative agreement with consumers, who agree to modify their consumption patterns in accordance with prevailing conditions. This dynamic approach to demand management contributes to optimizing system performance and ensuring efficient resource utilization.

The authors introduced a real-time voltage regulation framework that relies on demand response initiatives. This framework utilizes information gathered from Remote Terminal Units (RTUs) to identify optimal tap changer configurations and appropriate levels of load reduction when necessary (Zakariazadeh et al., 2014). Similarly, the authors investigated the viability of integrating an ITS with an intelligent load to promptly address voltage control and demand-side

management requirements in building settings (Luo et al., 2017).

The authors (Chen et al., 2015) investigated dynamic load response strategies incorporating electric springs to regulate voltage and frequency under the influence of variable wind energy. In a comparative study, the authors (Luo et al., 2015) examined electric springs and STATCOM, highlighting that electric springs offer superior voltage regulation performance in distribution systems compared to STATCOM. Addressing variability in PV power generation, the authors (Yao et al., 2016) proposed an independent load scheduling strategy to reduce peak demand and mitigate reverse power flow from PVs, thereby lowering voltage elevation.

Additionally, the authors (Saxena et al., 2024c) introduced a two-step DSM framework tailored for distribution networks with significant RES, emphasizing a centralized direct control approach for managing voltage oscillations, particularly with electric water heaters.

Table 14

Voltage regulation by BESS integration in DN.

Aspect	Description	Advantages	Applications	Challenges	Reference
BESS Integration	Integration of BESS for managing short-term and mid-term voltage fluctuations. BESS offers an environmentally friendly energy source, but long-term stability requires significant investment due to high costs.	- Provides essential reserves (up to 30 % of system needs) - Effective short-term voltage and frequency regulation. - Environmentally friendly energy storage solution.	- Systems with high renewable energy integration. - Voltage and frequency control in grids with significant renewable energy penetration. - Emergency backup power supply.	- High initial investment and maintenance costs. - Limited by battery life and capacity. - Long-term voltage stability requires large-scale investment in BESS infrastructure.	(Jiang et al., 2024)
Vanadium Redox Batteries for Voltage Fluctuation Management	Proposed use of Vanadium Redox Batteries to mitigate voltage fluctuations due to extensive integration of rooftop PV systems, with a planning framework to scale BESS for effective voltage variation management.	- Mitigates voltage fluctuations. - Scalable solution for managing increased PV penetration. - Environmentally friendly technology.	- Distribution networks with extensive PV integration. - Voltage regulation in grids with rooftop solar systems. - Centralized control of BESS for optimal performance.	- High cost of Vanadium Redox Batteries.- Complexity in scaling BESS to meet growing demand.- Requires robust control systems for effective operation.	(Nazaripouya et al., 2015)
Synchronized BESS Charging/Discharging Strategy	A synchronized strategy for charging/discharging BESS to minimize voltage and frequency fluctuations, with centralized control at a primary control center.	- Minimizes voltage and frequency fluctuations. - Centralized control ensures coordinated response. - Enhances grid stability with high RES penetration.	- Grids with high renewable energy penetration. - Centralized energy storage management. - Voltage and frequency regulation in distribution networks.	- High initial and operational costs. - Complexity in coordinating multiple BESS units. - Dependence on centralized control systems for effective operation.	(Jiang et al., 2022)
Coordinated Voltage Regulation with BESS	Coordinated voltage regulation strategy using dynamic droop control and BESS in active DC distribution networks with high PV penetration, aiming to optimize DG capacity.	- Effective voltage regulation in DC networks (up to 15 % improvement) - Optimizes DG capacity within distribution networks. - Enhances system efficiency and reduces losses.	- Active DC distribution networks. - High PV penetration areas. - Integration with dynamic droop control for voltage regulation.	- Requires advanced control systems. - High costs associated with BESS and control infrastructure. - Complexity in coordinating with existing grid systems.	(Li et al., 2024; Mohamed et al., 2024)

Researchers also conducted a comparative analysis on integrating RES-based DG into distribution networks (Saxena et al., 2022b).

The authors (Sapari et al., 2018) recently investigated load shedding strategies integrating DG into distribution systems, contributing valuable insights into effective implementation strategies.

Table 13 provides a comparative analysis of various DSM techniques utilized for voltage regulation in power systems. The table highlights the different DSM strategies employed to manage and control voltage levels within distribution networks, particularly in the presence of DG and RES.

5.7. BESS

Furthermore, the integration of BESS in power systems has gained attention as an environmentally friendly energy source capable of providing essential reserves to both the system and RES. BESS can effectively manage short-term and mid-term voltage fluctuations; however, long-term voltage stability requires significant investment due to the high costs associated with BESS (Jiang et al., 2024). The authors (Nazaripouya et al., 2015) proposed a solution using Vanadium Redox Batteries to mitigate voltage fluctuations induced by the extensive integration of rooftop PV systems.

The authors (Nazaripouya et al., 2015) introduced a planning framework aimed at scaling BESS to effectively manage voltage variations resulting from PV integration. The authors (Jiang et al., 2022) proposed a synchronized charging/discharging strategy utilizing BESS to minimize voltage and frequency fluctuations, centralizing control at a primary control centre. The authors (Li et al., 2024) investigated a synchronized approach for coordinating multiple BESS to mitigate voltage surges due to increased PV penetration.

Table 14 emphasizes the critical role of BESS in enhancing voltage

regulation, particularly in networks with high levels of renewable energy integration, by providing a reliable and responsive solution to voltage stability challenges.

The authors (Mohamed et al., 2024) conducted a comprehensive study integrating BESS to achieve goals such as voltage management, loss minimization, and peak load reduction, optimizing DG capacity within DNs. The authors (Krishan et al., 2017) addressed challenges posed by high PV penetration, presenting a coordinated voltage regulation strategy in active DC DNs using dynamic droop and BESS. Table 15 provides a taxonomy summarizing these studies on voltage regulation in DNs with DG presence.

6. Current challenges and suggestions

6.1. Current challenges

- **Incompatibility with Traditional Systems:** Traditional power systems were not designed to handle the complexities introduced by large-scale DG integration. This leads to challenges in protective systems and voltage regulation within DNs. The variable nature of DG outputs can disrupt established fault detection and isolation processes.
- **Fault Current Management:** The integration of DG units, especially those that generate power continuously, can alter fault current characteristics, including their magnitude and flow paths. This requires adjustments in protective relay settings and coordination schemes to ensure accurate fault detection and protection.
- **Voltage Fluctuations and Overvoltage Conditions:** DG units, particularly photovoltaic (PV) systems, can cause significant voltage fluctuations and potential overvoltage conditions when generating excess power. Managing these fluctuations is critical to maintaining

Table 15

Categorization of examined articles concerning the control of voltage in DNs with the inclusion of DGs.

Ref.	Problem Statement	Remedial Action
(Mogos and Guillaud, 2004)	Voltage regulation challenges in DG-incorporating networks	Controlling both active and reactive power of DG units
(Chalise et al., 2016)	Excessive voltage caused by miniature wind turbines	Dynamic adjustment of pitch angle to reduce WG output
(Ghosh et al., 2017)	Voltage rises with high DG penetration	Management of reactive power and restriction of active power for PVs.
(Zeraati et al., 2019)	Voltage drops during peak demand and rise from rooftop PVs	Active curtailment of power generation from PV arrays
(Su et al., 2014)	Enhancing unbalanced LV networks with PVs	Efficient reactive power regulation and active power reduction
(Liu et al., 2018)	Optimal system realignment and voltage-related issues	Effective utilization of voltage regulation devices
(Tian et al., 2016)	Voltage violations from DG penetration and load demand	Optimization of VARs and network reconfiguration strategies
(Hu et al., 2016)	Voltage rises from PV cells and imbalance	Leveraging transformers with single-phase tapping capabilities
(Muttaqi et al., 2015)	Voltage control with DC mechanisms in AC context	Introducing a structured coordination approach
(Salih and Chen, 2016)	Voltage regulation with DG integration	Coordinated operation of OLTC and management of reactive power in WG.
(Daratha et al., 2014)	Efficient regulation of voltage in systems with PVs that experience imbalance	Coordinated SVC and OLTC for enhanced control
(Mehmood et al., 2018)	Voltage rises due to widespread DG penetration	Synchronized functioning of OLTC, capacitor banks, and generators in coordination
(Zhang and Chu, 2017)	Voltage control in high penetration systems	Synchronized control strategy for PVs, BESS, and OLTCs
(Azzouz et al., 2017)	Advanced voltage regulation in operational DNs	Applying fuzzy logic to regulate OLTCs, PV systems, and WGs.
(Lee et al., 2013)	Regulating voltage in systems incorporating renewable DGs	D-STATCOM for the regulation of voltage
(Zad et al., 2013)	Voltage control in MV radial layouts	Coordinated D-STATCOM and OLTC management
(Kabiri et al., 2014)	Voltage control with the involvement of PV cells	Managing the inverter to inject reactive power
(Anantwar et al., 2017)	Regulating voltage using renewable DG and diesel engines	Managing the reactive power generated by PV inverters.
(Samadi et al., 2014)	Voltage increases from widespread PV use	Simultaneously synchronized control of reactive power and power fed into the system
(Collins and Ward, 2015)	Voltage increases in networks with home PVs	Control of real and reactive powers in distributed inverters
(Zakariazadeh et al., 2014)	Ensuring voltage control with fluctuating DG production	Emergency demand response and load reduction strategy
(Luo et al., 2017)	Voltage control with variable wind energy	Incorporating thermal energy storage using ice
(Chen et al., 2015)	Voltage and frequency management with intermittent wind	Employing electric springs programs
(Luo et al., 2015)	Control of voltage levels in DNs	Regulating dispersed electric springs
(Yao et al., 2016; Jiang et al., 2024)	Voltage rises from rooftop PVs	Demand-side management for energy consumption scheduling
(Jiang et al., 2022; Li et al., 2024)	Voltage and frequency fluctuations in networks	Implementing energy storage systems with distributed batteries

voltage levels within acceptable limits and ensuring the stable operation of the network.

- **Advanced Protection Strategies:** Traditional protection systems may not effectively address the new challenges posed by DG. The need for advanced protection strategies, such as DOCRs and adaptive protection schemes, is crucial to handle the altered fault current characteristics introduced by DG.
- **Voltage Regulation and Control:** Integrating DG requires sophisticated voltage regulation and control strategies. The variability in DG output necessitates dynamic adjustments in voltage levels to maintain stability and prevent overvoltage conditions.

6.2. Suggestions

- **Upgrade Protective Systems:** Implement advanced protective devices and strategies that can handle the variable nature of DG outputs. This includes the use of adaptive protection systems and DOCRs that provide localized fault detection and minimize disruptions.
- **Implement Smart Grid Technologies:** Deploy smart grid technologies that offer real-time monitoring and control of voltage levels. Smart grids can dynamically adjust voltage regulation in response to changing DG outputs and load conditions, improving overall network stability.
- **Enhance Voltage Regulation Techniques:** Utilize voltage regulation devices, such as STATCOMs and voltage regulators, to manage voltage fluctuations effectively. Incorporate these devices into a coordinated control strategy to address both overvoltage and under-voltage issues.
- **Develop Comprehensive Control Strategies:** Develop and implement comprehensive control strategies that integrate DG with existing grid management systems. This includes real-time data analytics and adaptive control techniques to optimize the performance of the grid under varying DG conditions.
- **Invest in Research and Development:** Support ongoing research and development efforts focused on innovative solutions for DG integration. This includes exploring new technologies and methodologies for enhancing protective systems, voltage regulation, and overall grid stability.

7. Conclusion

The integration of DG into power systems, especially at the LV level, is driven by the goals of improving system reliability, enhancing protection mechanisms, and increasing overall efficiency. DG technologies, such as solar and wind power, are seen as crucial for diversifying energy sources and reducing dependency on centralized generation. However, integrating DG into existing power grids presents a series of complex challenges.

One of the primary challenges arises from the fact that traditional power systems were not originally designed to handle large-scale DG integration. This mismatch can lead to issues in protective systems and voltage regulation within DNs. Protective systems, which are crucial for detecting and isolating faults to prevent damage to equipment and ensure safety, must adapt to the variable nature of DG outputs. The introduction of DG alters fault current characteristics, including magnitude and flow paths, necessitating adjustments in protective relay settings and coordination schemes.

For instance, DG units can contribute to fault currents during grid disturbances, affecting the operation of overcurrent protection devices. To manage this effectively, advanced protection strategies like DOCRs are increasingly deployed. These devices not only detect fault currents but also ensure that protective actions are localized to the affected area, thus minimizing disruption to the rest of the network.

In addition to protective concerns, integrating DG, particularly PV systems, can lead to voltage fluctuations and potential overvoltage conditions within DNs. This is because DG units, when generating

surplus power relative to local demand, can elevate voltages beyond acceptable limits. Managing these voltage variations requires sophisticated control strategies, including voltage regulation devices and smart grid technologies that can dynamically adjust voltage levels in response to changing DG outputs and load conditions.

Addressing these challenges requires a comprehensive approach that considers both protective system enhancements and advanced voltage control strategies tailored to the characteristics of DG technologies. Research and development efforts are increasingly focused on developing adaptive solutions that can accommodate higher levels of DG penetration while maintaining grid stability and reliability.

In conclusion, while the integration of DG offers significant benefits in terms of sustainability and energy diversification, it necessitates careful consideration of its impact on protective systems and voltage control mechanisms within Distribution Networks. By addressing these challenges proactively, stakeholders can ensure that DG integration proceeds smoothly and contributes positively to the resilience and efficiency of future power systems.

8. Future perspectives

Looking ahead, the integration of DG into power systems is expected to grow, driven by the increasing adoption of renewable energy sources and advancements in technology. Future perspectives include:

- **Increased Penetration of Advanced DG Technologies:** As technology advances, the penetration of sophisticated DG technologies, such as next-generation PV systems, advanced wind turbines, and energy storage systems, will become more prevalent. These technologies will require continued adaptation of grid management and protection strategies.
- **Evolution of Smart Grid Capabilities:** The development of smart grids will play a critical role in managing the complexities associated with high levels of DG integration. Future smart grids will feature enhanced communication, automation, and control capabilities to effectively handle dynamic grid conditions.
- **Integration of Artificial Intelligence and Machine Learning:** The use of artificial intelligence (AI) and machine learning (ML) will become increasingly important for predictive analytics and real-time decision-making in grid management. AI and ML can optimize grid performance by predicting DG output variations and adjusting control strategies accordingly.
- **Enhanced Collaboration and Standardization:** Greater collaboration among stakeholders, including utilities, technology providers, and regulators, will be essential for developing standardized approaches to DG integration. Standardization will help ensure compatibility and interoperability among various DG technologies and grid management systems.
- **Focus on Resilience and Sustainability:** Future developments will prioritize enhancing the resilience and sustainability of power systems. This includes building more robust and adaptable networks that can withstand and recover from disruptions while maximizing the benefits of renewable energy sources.

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CRediT authorship contribution statement

Mohammed H. Alsharif: Writing – review & editing, Investigation, Conceptualization. **Mun-Kyeom Kim:** Writing – review & editing, Funding acquisition, Conceptualization. **Praveen Kumar:** Investigation,

Conceptualization. **Bhupender Sharma:** Visualization, Supervision. **Saurabh Kumar Rajput:** Supervision, Project administration. **Vivek Saxena:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saibal Manna:** Supervision, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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