Review

Security Impacts Assessment of Active Distribution Network on the Modern Grid Operation—A Review

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Abstract: The future grid will include a high penetration of distributed generation, which will have an impact on its security. This paper discusses the latest trends, components, tools, and frameworks aimed at 100% renewable energy generation for the emerging grid. The technical and economic impacts of renewable energy sources (RES)-based distributed generation (DG) on the emerging grid security are also discussed. Moreover, the latest approaches and techniques for allocating RES-DG into the distribution networks using specific performance indices based on recent literature were reviewed. Most of the methods in recent literature are based on metaheuristic optimization algorithms that can optimally allocate the RES-DGs based on the identified network variables. However, there is a need to extend these methods in terms of parameters considered, objectives, and possible ancillary support to the upstream network. The limitations of existing methods in recent literature aimed at ensuring the security of the integrated transmission-active distribution network under high RES-DG penetration were identified. Lastly, the existing coordination methods for voltage and frequency control at the transmission and active distribution system interface were also investigated. Relevant future research areas with a focus on ensuring the security of the emerging grid with high RES-DG penetration into the distribution networks are also recommended.

Keywords: renewable energy; security assessment; distributed generation; emerging grid

1. Introduction

Fossil fuel-based power generation has raised serious global environmental concerns due to the excessive amount of emission it contributed, thereby depleting the ozone layer and resulting in many more consequences. The increase in CO_2, which is a major greenhouse gas (GHG), has been predicted to hit 45 billion metric tons by 2040 [1]. About 77% of GHG comes from power systems and industries. Some power systems are driven by safety while some are driven by economics. Economics-driven power systems are occasionally operated close to their security limits. Occasional overloading of the transmission lines, voltage stability issues, system frequency fluctuations, power quality issues, and large active and reactive power losses are some of the challenges faced by the present grid. Many blackouts have been reported as a result of insufficient generation and transmission capacities coupled with the weakened transmission infrastructure and aging components [2]. With the global power demand being estimated at around 770 TW by the year 2050 [3], the present grid may be incapable of supporting the future power system requirements and dynamic load growth within the required security limits.

In addition to reducing the carbon footprint of the power generation, the incorporation of renewable energy generation into the present grid can significantly improve its performance and reliability. Policies have been adopted by several countries in line

with the millennium development goals regarding the environment and global warning to significantly increase the amount of power generation from renewable energy sources. The successes claimed by many countries on high penetration of renewable energy power generation may be attributed to small and isolated grids with relatively small loads. In addition, in many scenarios, power is generated through big hydro and geothermal plants. These power generation systems may be considered as a central generation where penetration of distributed generation (DGs) systems will have no significant impact on the security of the grid. Major security challenges emerge at high penetration of renewable energy sources distributed generation (RES-DG) into the grid.

The benefits of RES-DGs are contingent on the optimal planning and operation of the appropriate type of RES-DG. With advancements in power electronics, modern RES-DGs do not only generate energy but also provide the system operators with new capabilities to support the transmission system. Several RES-DGs can be aggregated and operated as virtual power plants (VPP) to provide frequency control under contingencies. Optimal planning of RES-DG involves the allocation and penetration levels into the distribution systems. Optimal allocation of RES-DGs reduces the power loss within the distribution system and also improves the distribution network voltage profile.

Unlike the conventional distribution network, which merely receives power from a transmission or sub-transmission network, an active distribution network has a power generation within it. The active distribution network operators proactively manage medium and small-scale renewable energy and non-renewable energy source DGs to achieve efficient operation. High penetration of RES-DG may increase power quality issues and protection challenges within the active distribution system. Considering that the emerging power grids will contain high penetrations of RES-DGs, it is therefore important to employ support technologies and schemes to limit the negative security impacts. Enabling and support technologies include improved energy storage systems (ESS) and enhanced communication systems. Coordination schemes between the transmission network and active distribution networks for voltage and frequency controls will ensure the security of the emerging grid. Through these support tools and schemes, the emerging grid may be able to operate securely under high penetrations of RES-DG.

To this end, this paper is focused on issues surrounding the high penetration of small renewable energy generation into the distribution systems where the impacts on the grid's security are significant. The contributions of this paper include:

- A comprehensive technical discussion on the trends of energy storage systems (ESS) and other supporting components in the quest for a 100% renewable energy grid.
- A review of the existing techniques, optimization objectives, and algorithms for optimal RES-DG allocation in the literature within the last 10 years.
- A review and analysis of existing voltage and frequency coordination techniques to support the increased penetration of RES-DGs.

The rest of this paper is organized as follows. Section 2 discusses the role of renewable energy sources in the power grid transition. In Section 3, the technical impacts of high penetration of RES-DG into the grid are discussed. The review of existing methods and techniques to limit the impact of RES-DG penetrations is presented in Section 4. Section 5 discusses and reviews the trends in technology and tools to ensure the security of the grid under high penetrations of RES-DG. Section 6 contains the conclusions from the reviews and the recommendations for future research areas based on the limitations of the existing techniques.

2. Grid Transition

Over the last two decades, the number of power system blackouts has continuously increased [2,4]. This increase is a result of continuous load growth and the challenges in the transmission/distribution systems. One of the immediate solutions to reducing the number of blackouts is to increase investments in all the subsystems of the grid. Consequently, deregulation and decentralization policies were adopted to encourage private

sector participation, thereby increasing investments in the power grid. Deregulation of the electricity market is aimed at improving the reliability and efficiency of the grid from the network planning stage to network operations. Before decentralization, central generation (CG) and centralized control have been the major power generation and control methods, respectively. Under the CG method, large generating stations are sited remotely from bulk consumers but close to their turbine drive source due to environmental and economic constraints. The power generated is instantaneously transported via long transmission lines to the consumers. Although not a new concept, distributed generation (DG) methods have acquired extensive acceptance due to grid decentralizing as well as the disadvantages of CG in terms of high power loss and investment cost. DG methods are therefore intended to reduce the cost of power delivery and enhance the reliability of power despite the load growth. The pros and cons of the CG and DG methods considering technical and economic impacts are extensively discussed in [5].

2.1. The Emerging Power Grid

The emerging grid is envisioned as an integration of smart components, networks, and subsystems under decentralized control to provide benefits for consumers and utilities. At the subsystem level, the emerging grid may be realized or classified into smart infrastructure subsystem, smart information subsystem, smart protection subsystem, management subsystem, and smart data communication subsystems. The infrastructure subsystem is responsible for the secured bi-directional flow of power and information between the producers, consumers, and control systems. The major unit in this subsystem is the smart energy, which consists of the smart generation, transmission, and distribution units [6]. The smart generation units will harness the potentials of renewable energy sources distributed generation systems. The aggregation of RES-DGs advances the concept and feasibility of virtual power plants (VPP). Virtual power plants are DGs with an aggregated capacity equivalent to the large CG systems. The concept of VPPs provides extra benefits such as reliability, flexibility, and quick response to fluctuations compared to CGs. However, the operation and control of VPPs require complex techniques to become beneficial [7].

The emerging power grid will include high penetration of RES-DGs due to economic, environmental, and technical reasons. RES-DGs are classified from small (micro) to large-sized renewable energy source power generators sited close to the consumers, thereby eliminating the need for long transmission, and significantly reducing power losses. RES-DGs are tied to the grid through electronic converter systems due to the absence of rotating mechanical inertia. Consequently, they are often regarded as non-synchronous generators. Table 1 gives a summary of the types of DGs with related characteristics of the RES type, energy storage, and compensation systems by unit capacities.

Table 1. Summary of distributed generation by capacity [8].

Classification	Capacity	RES Type	Active Power (P)	Reactive Power (Q)	Example
Micro DG	1 W to < 5 kW	A	+	0	PV, Battery, and Fuel cell
Small DG	5 kW to < 5 MW	B	0	±	Condensers and capacitors
Medium DG	5 MW to < 50 MW	C	+	+	Mini hydro
Large DG	50 MW to < 300 MW	D	+	−	Wind turbine

+ Generate − Absorb.

The strong correlation between global power demand and CO_2 emission forecasts necessitates the shift in the power generation framework. This framework change is aimed at reducing the fossil fuel-based power supply to achieve the global vision in response to climate change. Renewable energy sources (RES)-based distributed generation (DG) provides the best solution for future power generation considering the technical and environmental challenges. Several countries have designed and adopted policies to gradually increase the penetration of the RES-DG in respective power systems. Figure 1 shows the total global installed and available capacity of power generation from RES-DG

by leading countries, as of 2017. Despite China, Germany, and Japan having the largest installed and available capacities, Spain and India have the relative highest proportion of available-to-installed capacity. The persistent question, however, is how to ensure the security of the emerging grids with significantly increased levels of RES-DG clusters into the distribution networks.
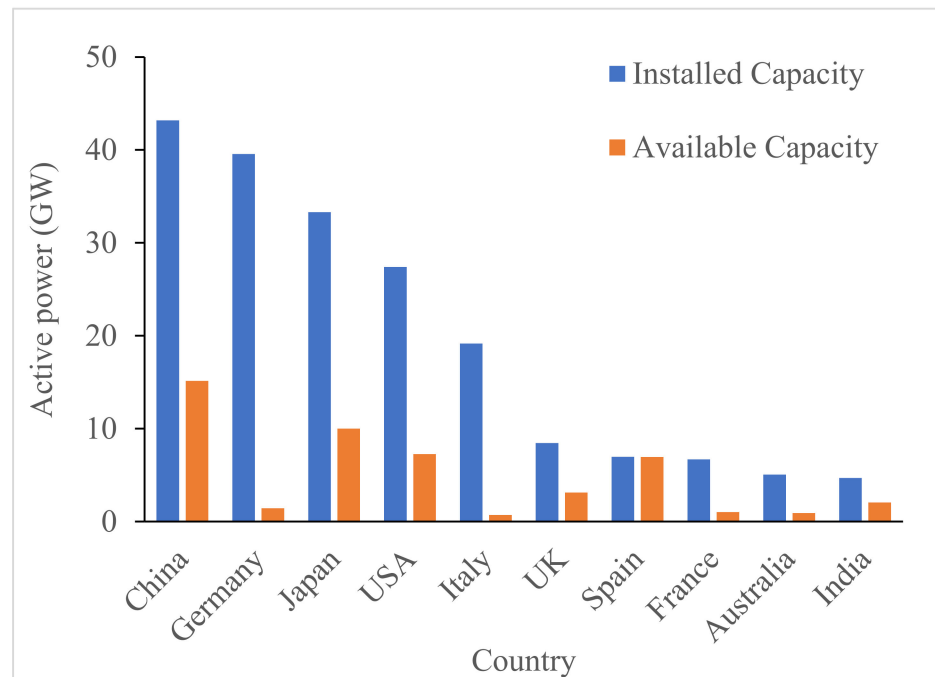

Figure 1. DGs installed and available capacities by leading countries [9].

Several terms such as smart grid, future grid, and intelligent grid have been used to describe the emerging power system. Simply put, the emerging grid entails a transformation from the conventional grid framework to an information-controlled, data-enabled, and highly interconnected network between producers and consumers of electric power embracing new technologies in transmission, distribution, and generation [10]. The objective is to operate a network to provide abundant, affordable, clean, efficient, and reliable power. The expected benefits of the emerging grid are not limited to reliability and efficiency improvements, but also include a strategic contribution to reduce global carbon emissions. The drivers of the emerging power grid can be categorized into network decentralization, generation decarbonization, and information digitalization, as shown in Figure 2.

Decentralization of power generation through distributed generation systems and energy storage systems reduces the power losses and subsequently the cost of power delivery. Renewable energy systems and electric vehicles are aimed at reducing greenhouse gases' contribution from power generation and transportation, respectively. However, indiscriminate and uncontrolled charging of large numbers of electric vehicles increases the load on the network and causes stress on the grid. Charging models and algorithms have thereby been proposed to limit the impact of EVs on the grid [11]. The modern grid will also take advantage of the availability of IoT devices and advancements in artificial intelligence algorithms for operation prediction. The security problems of the grid due to threats and attacks will also be limited due to modern security and blockchain technologies. The physical components of the emerging grid must be well integrated and coordinated through the distributed control centers. The control centers of the modern grids will be capable of ultrafast data acquisition, processing, and command redistribution. Moreover, the control modules will be expandable, scalable, and adaptable to changing architecture, services, and tools [12].
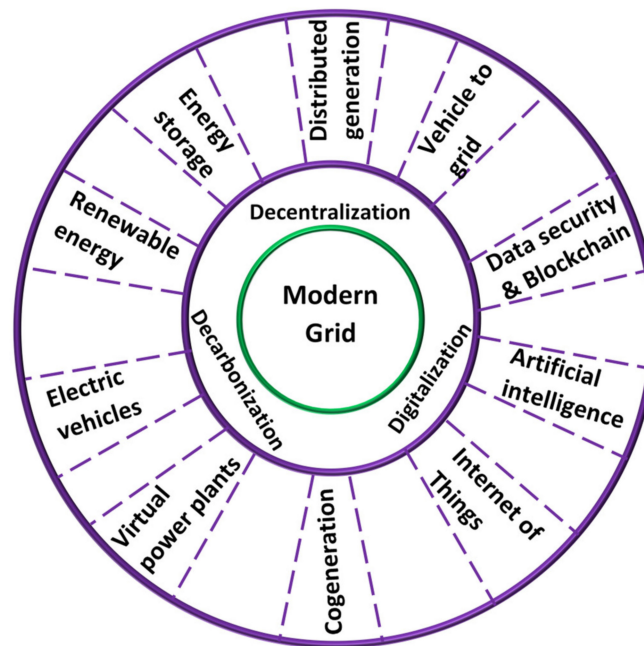
Figure 2. Drivers of the future power grid.

Another description of the emerging grid is the concept of a digital grid. The grid is divided into smaller units called grid cells, which will be connected by digital routers. This is similar to the energy ethernet model. The following three key technology capabilities are crucial for these models to be feasible: the plug-and-play interface, information router, and an open-ended utility program [13,14]. While there is significant progress in the applications of solid-state transformers (SSTS) as energy routers, the RES-DGs must also be able to operate in the plug-and-play mode. The ability of small, distributed resources and storage systems to operate in the plug-and-play mode will improve the resilience of the grid in terms of demand response, grid resilience, and restoration. The multi-criteria optimization problems proposed for grid restoration after major blackouts will also be significantly simplified if the major grid components can operate in the plug-and-play mode.

Power delivery will be achieved through an integrated transmission system–distribution system (TS/DS) consisting of FACTS devices, HVDC systems, voltage control devices, synchro phasors, and communication devices. The operators for each network within the integrated grid must operate within guidelines and code specific to the responsibilities which are aimed at achieving efficient power delivery. Figure 3 shows an example of the emerging grid consisting of large renewable energy generations, distributed renewable energy generation, and electric vehicles. The electric vehicles can also interact with the active distribution networks in the vehicle to grid (V2G) mode, thereby supporting the grid during peak load demand periods. The coupling point for the renewable energy generation systems to the grid depends on the type and generation capacity.

The function of the emerging grid includes bi-directional power flow between multiple voltage levels within a highly meshed network structure consisting of integrated AC and DC networks. Voltage and frequency control strategies in this multi-level model will be more complex compared with the single-voltage level AC-AC network within a grid. Research has been carried out to improve the efficiency of converters for this meshed model including HVDC and super grids [15]. A large part of the papers examined in [16] aimed to enhance the converters for bi-directional power flow control to ensure security and to improve the power quality in a high RES-DG penetrated environment. The distribution systems already have distribution FACTs devices (D-FACTS) designed to provide voltage support and power flow control at the medium voltage (MV) and low voltage (LV) levels. Therefore, as the idea of an integrated AC-DC grid develops, it is necessary to have the

DC version of flexible AC transmission systems (DC-FACTS) [17]. The meshed AC-DC grid will be configured to operate in a fully accessible model for small-scale RES-DGs and storage technologies for cost-effectiveness and effective consumer participation. To ensure the efficient operation of emerging integrated networks, and to achieve the goal of RES-DG and energy storage penetration, there is a need to develop a reliable integrated network management system for hybrid AC-DC power flow.
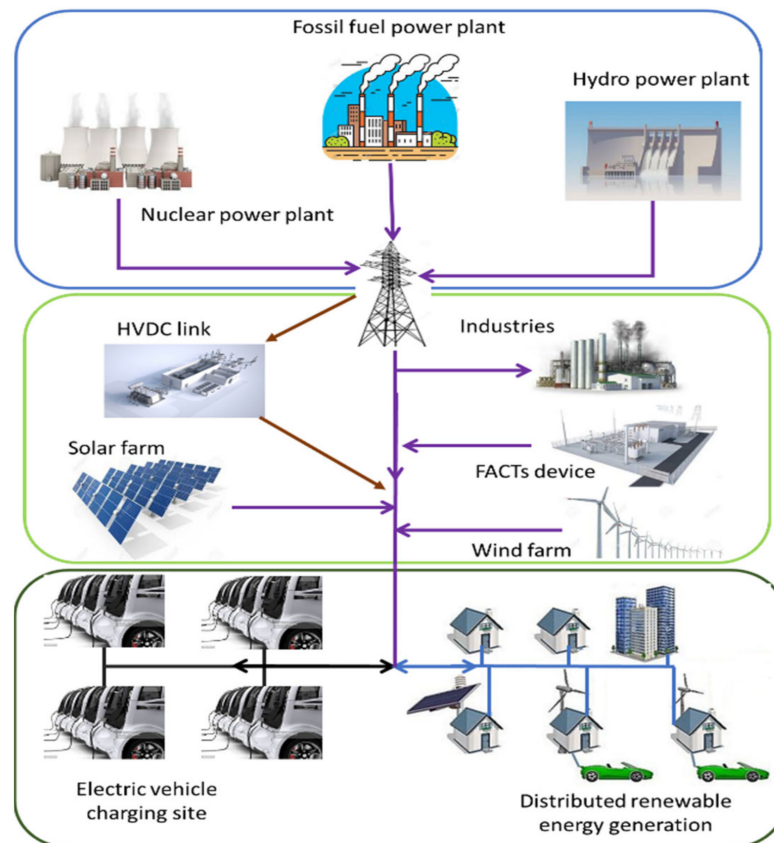

Figure 3. Model for the emerging power grid.

2.2. The Role of Renewable Energy Source in the Emerging Power Grid Architecture

As the demand for clean and efficient energy increases, a significant amount of renewable energy source (RES)-based distributed generation (DG) will be added to the grid. The model of the modern grid is based on the architecture of highly interconnected networks with the underlying component of the penetration of RES-DG systems. Synchronizing the operations of the RES-DG systems with the grid will ensure the future grid's security. Solar PV, wind turbine, and hydro (mini) systems represent the bulk of RES-DG that is significantly viable for power generation. Figure 4 provides a characteristic comparison of RES-DG using availability factors, environmental impact, and cost-benefit considerations. The unlimited supply and the cleanliness of the renewable energy sources are underlying positive factors across the types of renewable energy systems. However, the high construction cost of units of renewable energy systems is also a common factor to be considered at the active distribution network planning stage.

The applicability of RES-DG on the emerging grid considering scenario peculiarities is summarized in the model in Figure 5 showing a wide range of factors influencing the role of DG in future power systems. The security for a grid determined by the RES-DG penetration level, network configuration, and operation will be influenced by the weight attached to the choice factors.
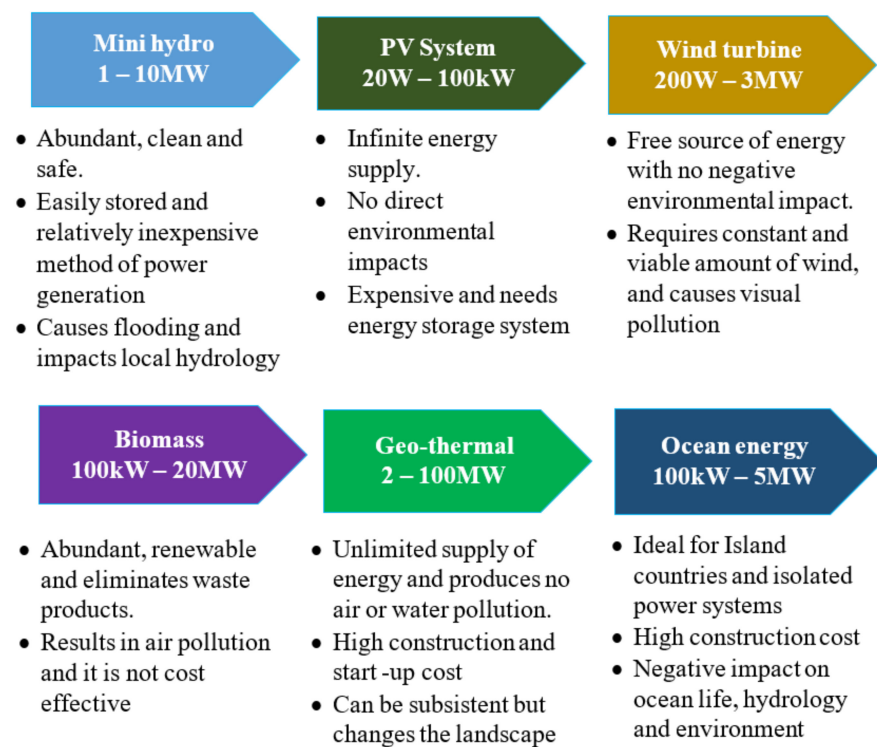
Figure 4. Renewable energy considerations [18].
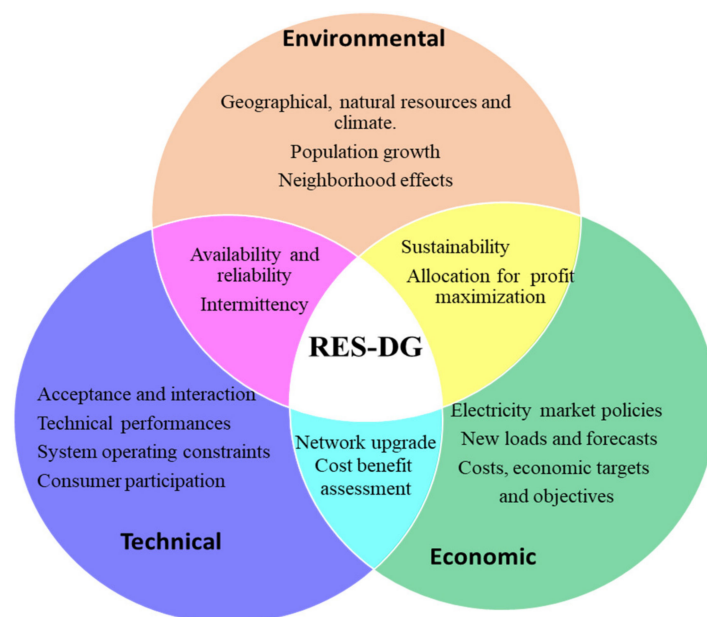
Figure 5. Factors influencing RES-DG penetration.

While it is certain that renewable energy systems will significantly reduce the power generation from fossil fuel-based generating plants, thereby reducing the greenhouse gases emissions, there are other environmental factors to be considered. Animals are removed from their natural habitats to acquire large landmasses for both PV and wind systems. The usage of a large area of land for PV and wind systems to generate a considerable amount of power also distorts the landscape. Furthermore, several bird species have been declared endangered after being killed by the rotors of wind turbines. Activities on the rivers and oceans have also been noted to disturb the ocean lives and may unbalance the natural order of life. The main economic factors considered among several others are the cost of

power generation and the purchasing power of the consumers. In addition, incentives from governments and the subsidization of the initial construction costs and price of energy are taken into consideration. The technical factors considered are the impacts of renewable energy systems on the grid's security, reliability, and protection. The decisions based on the technical factors are vital due to the inherent characteristics of the renewable energy sources generation systems.

The power output of RES-DG clusters depends on the efficiency of the units. With the efficiencies of wind turbine generators now significantly improved, the efficiencies of the solar PV panel will also increase from 12–19% to about 30–35% under favorable conditions [19]. The total installed capacity from renewable energy sources globally has increased by 50% between 2019 and 2020 [20]. The European Union has revised its proposed renewable energy source penetration target from 27% to 32% by 2030. These values are expected to increase with the global increase in load demand. In line with the global millennium developmental goals concerning climate change, ref. [21] discusses cases of substantial levels of RES-DG penetration and arguments for a proposed increment in the future.

Many existing small and isolated power systems have already integrated renewable energy source generation. Penetration levels above 30% have been reported for many isolated power systems (IPS) [22]. The high penetration level is due to the certainty of achieving significant technical and economic benefits from a relatively small investment in renewable energy. Renewable energy generation has been employed in scenarios where electrification of islands through the HVAC and HVDC transmission system are not economically viable. With diesel generators as backup, many islands from developed countries are powered solely by renewable energy sources. Countries with large power grids such as China, the USA, Brazil, and many countries in Europe including France and Germany have established policies supporting the penetration of renewable energy generation into their respective grids. China is the leading country with policies enhancing the rapid penetration of small and large renewable energy generation systems. One of the several policies is to encourage individual consumer rooftop PV installations. China's total rooftop solar capacity was reported at 5.27 GW in 2020, with total solar installations expected to reach 28–34 GW by the end of 2021 [23].

A leading country in rooftop solar photovoltaics (PVs) manufacturing, Germany has proposed increasing its solar and wind capacity from 120 to 215–237 GW after the withdrawal from the nuclear energy program. The renewable energy generation program has committed to 65% and 80% renewable energy of the total electricity demand by the year 2030 and 2050, respectively [24]. To realize this level of penetration, the German government has continued to subsidize the costs associated with the installation of RES-DG for consumers [25]. The installed generation capacity of Brazil reached a total of 162.8 GW in the year 2018 out of which 83.3% is renewable energy. From the total installed renewable energy generation, 22.6% is penetrated into the low voltage networks. With the electricity demand forecast at about 300% increase from the year 2013 to 2050, the penetration levels of wind power and solar power are projected to increase to 13.4% and 97%, respectively, by the year 2026 [26]. For smaller power grids, the highest renewable energy sources distributed generation penetration of over 45% is recorded for Denmark. Renewable energy distributed generation also accounts for about 20% of the total electricity generation in Spain and Sweden [27].

3. Technical Impacts of RES-DG Penetration

The high penetration of RES-DG integration into the distribution network will significantly alter the structure of the network. Renewable energy sources distributed generation system transforms a traditionally passive distribution network into a multi-source active distribution network. The right RES-DG penetration into the distribution networks will reduce the overall network losses and enhance the voltage profile. The utilization of RES-DG by distribution system operators to manage the variability and uncertainty of

demand and supply across different timescales is another advantage. This demand-supply management process is referred to as grid flexibility [28]. These flexibilities include network peak load shaving, load shifting, and valley filling [29]. The impacts of RES-DGs' penetration in the active distribution network and the connected upstream network are shown in Figure 6. The positive impacts of RES-DGs in this paper are discussed under the performance index. The most considered performance indices are voltage stability, reliability, and power loss. The negative impacts of RES-DGs are discussed under the power quality and protection challenges. Power quality challenges are mostly due to the variability of solar irradiance and wind velocity as well as the absence of mechanical inertia in RES-DG systems. Protection challenges are due to the absence of fault current limiting capability of RES-DG converters.
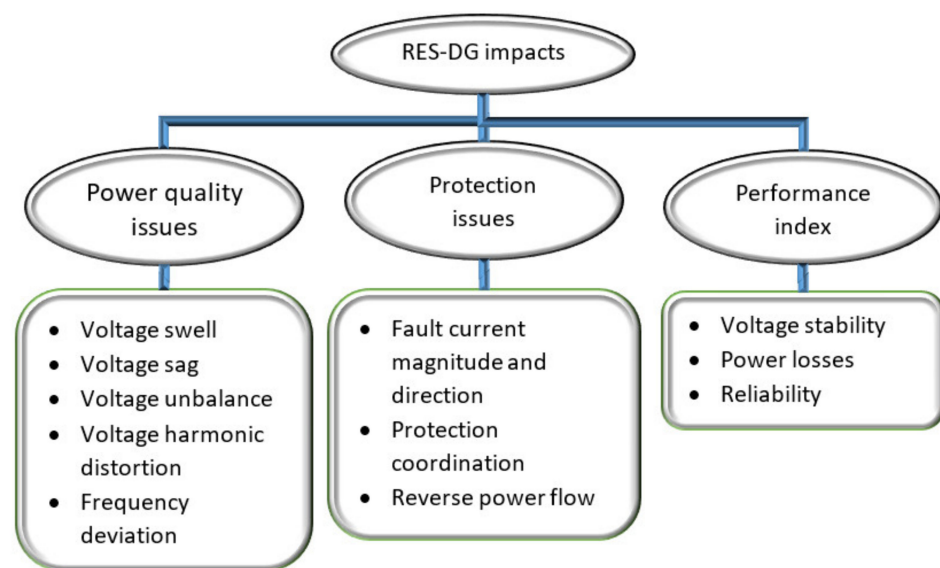
Figure 6. Technical impacts of DG penetration.

3.1. Power Quality Issues

Penetration of RES-DG reduces the overall system inertia as the synchronous generators are replaced by non-synchronous generators. Although the frequency of the network and its derivatives are rarely affected at low penetrations of RES-DG, some results in the literature have proved that the rotor speed deviation, rotor speed oscillation duration, and deviation of electrical frequency increase due to the reduced inertia [30–32]. Research on the penetration of RES-DG is mostly developed under power loss and voltage objectives. Modern wind turbines are equipped with voltage control features through sophisticated power electronics, which enables them to function as a conventional utility generator regarding voltage support for distribution and transmission systems. Consequently, the focus should be on frequency response, which is significantly impacted due to the reduced overall mechanical inertia. The stochastic characteristics of RES-DG and load variability necessitate the consideration of the local voltage and frequency constraints during active distribution network planning. To minimize the occurrences of local frequency instability, the penetration of RES-DG into the distribution network should be based on the grid's power-frequency characteristics. Additionally, the boundary of penetration of RES-DG should be defined under different scenarios of generation fluctuation and reserve capacity [33].

Another challenge of the high penetration of RES-DG on the active distribution network is its impact on the voltage and its waveform. The impact on voltage can be grouped into temporary voltage change and voltage step change. Temporary voltage change, which includes voltage sags and swells, is caused by the sudden drop in the root mean square (RMS) voltage and is characterized by a slow recovery to a new steady-state

voltage magnitude. Voltage sags and swells mostly occur during the fault period in the distribution network with large loads. The voltage step is the rapid changes in RMS voltage levels due to changes in active and reactive power levels. Voltage step usually follows system switching, unintentional islanding, unplanned outage of loads, unplanned outage of reactive power compensators, and line contingencies [34]. The overall power factor from a cluster depends on the instantaneous power scheduled from the different RES-DG types. Voltage step constraints have the greatest impact at lagging RES-DG cluster power factors, while operation at leading power factor tends to minimize the voltage problems [35]. Under the requirements of ANSI C84.1-2011 1995 from the IEEE Standards Coordinating Committee 21, the operations of DG should not cause voltage instabilities within the distribution network, at the point of common coupling (PCC) of clustered RES-DGs, and the TS-DS interface [36]. This is critical for time-varying voltage-dependent loads, which are usually ignored by most studies. The impact of high penetration of DG on the voltage waveform is discussed under the voltage harmonics distortion. Voltage harmonics distortion, which is caused usually by the electronic converters in the network, has also been predicted to increase with load growth. The voltage step is an important index that has been overlooked by studies focused on the allocation of RES-DGs. Harmonic distortion levels also limit high RES-DG penetration. Little attention has been given to the harmonic injection into the transmission network through the TS-DS interface occurring at the point of common coupling (PCC). The permissible level of harmonics distortion caused by inverter-based DGs is regulated in IEEE-519-1992 standards.

To overcome voltage stability issues limiting maximum RES-DG penetration, several practical scenario-based methods may be employed. These methods include adjusting the secondary winding of LV transformers, giving priority to reactive power absorbing DGs, RES-DG power curtailment, reducing line impedances, and storage of the excess power [37]. Due to engineering and physical design constraints, some of the techniques may not be practicable and applicable to all distribution networks. Therefore, it is desirable to develop a generic approach that integrates the network dynamic limits for active distribution network planning and operations. Such an approach will include parameters that will be categorized into one or more of the following limits: static element limits, generation, and demand seasonal limits, static and dynamic system stability limits, as well as operator-specific limits. Some of these limits are obtainable through real-time systems, while others are obtainable using forecast models. For example, the impacts of passing clouds and sudden changes in wind parameters should be considered in the inter-hour scheduling under the seasonal generation limits.

The overpenetration of RES-DG within an active distribution network occurs when more power is generated from RES-DG than scheduled. Power curtailment and storage are traditional approaches that have been used to limit the amount of power from DGs. Flexibility utilization techniques are also becoming common for managing RES-DGs generation levels by system operators. The flexibility obtained through RES-DG penetration may be extended to the transmission system through the aggregators. The challenge here lies in the complex computation involved in the inter-network-operation modeling, and the representation of the flexibility operating region due to generation variability and network limitations [38].

3.2. Protection Challenges

The impact on the protection system depends on whether the DG is synchronous or non-synchronous, as well as the DG penetration level. The challenge for the protection systems is the unintended reverse power flow from the active distribution network to the upstream medium voltage network when the RES-DG is at peak power generation during off-peak load demand periods. The surplus current is perceived by the relays as fault current within the network. This misinterpretation of fault current may cause unintended islanding within the network. Different types of DGs have different short circuit characteristics to which the protection systems must effectively respond under

predictable and unpredictable fault conditions. In addition, the degree of protective failure is determined by the DG's size. Refs. [39,40] demonstrated the changes in short circuit current due to different DG penetration levels for a three-phase short circuit fault at different positions from the DG.

Traditionally, distribution networks are radial by design, and the protection schemes are designed for a single-source power supply from the transmission system. The penetration of DGs is more promising in loop network configurations. Therefore, the functioning of modern protection schemes is inclined toward loop applications over radial applications [41]. In the loop protection schemes, a relay may malfunction due to tie switch operations and bidirectional current flow. A new protection scheme capable of fast fault location and fault section isolation in a loop network is proposed in [42] to achieve the protection of the modern power grid. Protection devices with a simple design and time–current characteristics have effectively performed the tasks of protection from overcurrent in both radial and loop configurations. However, with the RES-DGs also contributing to the fault currents in the emerging distribution network, the traditional protection, which assumed unidirectional flow of current, will no longer be effective. The variability and unpredictability of DGs may increase the loss of coordination of the existing protection devices. Moreover, fault levels will be increased, and varying fault currents will further compromise the protection coordination. Ref. [43] concluded that the deviations in the local node frequencies increase with the high RES-DG, thereby reducing the precision of the fault location algorithms.

The loss of protection coordination has negative impacts on the reliability of the distribution system. The study in [44] shows that the reliability of the traditional distribution system is degraded significantly by the loss of protection coordination resulting from the high penetration of RES-DGs. Protection blinding and sympathetic or false tripping have been identified as the two most common causes of miscoordination. Blinding occurs when the sensitivity of a protective relay is reduced. The fault currents seen by the upstream protective devices will be reduced by the presence of a RES-DG located downstream. The equivalent fault current will depend on the short circuit impedances of the main source and the RES-DG as well as the impedance of the feeder to the point of fault. Sympathetic tripping occurs when a protective device in a feeder operates for a fault outside its protection zone mostly in another feeder. This tripping happens when the protection device's precision is lost as a result of reverse current from the RES-DG toward the fault location [45].

Several techniques for new protection devices' design for the emerging grid have been recommended in [46]. These techniques can be classified under non-traditional fault identification and new relay characteristics development. Communications-based solutions that attempt to detect and locate faults within the active distribution network are becoming common. The appropriate circuit breakers are then identified to trip and clear the fault. A new relay characteristic for the protection system was proposed in [30] based on the inverse operating time vs. line admittance characteristics. This new characteristic enhances the sensitivity of the relay for precise fault location on the feeder. These new relays can also be coordinated similarly to the existing simple time–overcurrent relays [46,47].

3.3. Performance Indicators

Voltage instability, which occurs frequently as a result of increasing load demands and limited transmission capacity, is alarming and has been a source of concern for power system operators [48]. Voltage stability is the ability of networks to maintain acceptable voltages at all network nodes under normal operating conditions and after being subjected to disturbances. The inability of a network to supply the reactive power demand is a major contributor to voltage instability. The assessment of voltage stability is carried out under dynamic and static stability studies. Dynamic voltage assessment produces the voltage response of a system to a sequence of discrete events in the time domain [49]. Static voltage assessment involves the identification of critical network nodes, evaluation of load

margins, and estimation of reactive power compensation [50]. Voltage instability is a local challenge to distribution system operators because it is a global challenge to transmission system operators.

Several voltage stability indices (VSIs) have been proposed in the literature for voltage stability assessment. Some of these indices may be used to detect the weak lines and buses in the network as well achieving optimal RES-DGs allocation. The available voltage stability indices can be grouped into the Jacobian matrix-based indices and system variable-based indices [51]. The system variables-based indices can be generalized into the line voltage stability indices (LVSIs) and bus voltage stability indices (BVSI). The LVSIs are based on the reduced two-bus network representation and are used to evaluate the weak links with potential voltage problems in the network. The BVSIs are indices derived from nodes' voltage deviation, which is caused by reactive power demand and supply imbalance [52].

The penetration of RES-DG units into the distribution networks provides several benefits such as improving voltage profiles and load factors. To achieve these benefits, the RES-DG must be optimally sized and sited on a specific node in the network. Installing RES-DGs units in non-optimal locations may lead to voltage instability of the network. The proposed techniques and algorithms for optimal placements of RES-DGs are discussed in Section 4.1.

The bulk of power loss from generation to utilization has been attributed to the transmission and distribution networks. Therefore, power loss reduction is considered a key objective during the planning of active distribution networks considering RES-DG penetration. Since high power loss contributes to the high cost of power delivery, there has been a considerable increase in research aimed at reducing active power loss in the distribution network employing RES-DGS. It is economically and technically impractical to have active and reactive power support on every node in the distribution network. Therefore, an optimal site and size of RES-DG must be selected to maximize the benefits. Because the relationship between the RES-DG penetration level and power loss follows an inverse quadratic function trajectory [53], a non-optimal allocation may therefore lead to an increase in power loss. Although it is usual to combine power loss objective with other performance indices in a multi-objective RES-DG allocation problem, techniques for power loss minimization as a single objective optimization problem is also common. The benefits of existing techniques in a single objective problem over a multi-objective problem for power loss minimization using RES-DGs are unclear and highly doubtful [54]. With a focus on power loss minimization, heuristic techniques were proposed in [55–57] in a multi-objective optimization model.

Reliability is another important index in measuring the performance of an active distribution network with RES-DG penetration. Traditional methods of evaluating reliability are based on deterministic conditions, which rely on past system experiences. These methods do not consider the probabilistic nature of outages that may be caused by RES-DGs. It is also impractical for new active distribution networks due to the lack of historical reliability data. In addition, deterministic methods are focused on specific reliability indices. However, with these indices, it may be impossible to explicitly express the performance of the network [58]. Research has consequently moved from deterministic approaches to stochastic approaches, which are based on the summary of statistical data on the individual components within the system.

The Markov process and Monte Carlo simulation are the two common methods available for stochastic reliability assessment of systems. A large amount of simulation and time needed to estimate the average of the reliability in the Monte Carlo method makes it less preferable to the Markov process. In the Markov method, several reliability indices may be quickly evaluated using the systems' state space [59]. The reliability of an active distribution network varies with the point of connection of the RES-DG on the feeder. Under the emerging deregulated system with increased competition for market share from operators, it is highly important to ensure good reliability. Refs. [60–62] focused on the distribution network planning and expansion using optimal RES-DG placement to

maximize the distribution network reliability. At lower penetration, RES-DG improves the reliability of the distribution networks, specifically when reliability is evaluated using the availability index. However, the overall reliability of the grid could be compromised at high penetration levels [63].

4. Recommendations to Limit Security Impacts

4.1. Active Distribution Network Planning

Probabilistic active distribution network planning techniques, which enable a better risk assessment under realistic conditions for optimal RES-DG penetration level assessment, are becoming common [64]. Probabilistic modeling methods were proposed in [65,66] based on solar PV generation and load uncertainties. An effective probabilistic planning model will be adaptable to several RES-DG types and network configurations. In addition, it should consider the impact of environmental factors on the performance of the RES-DGs. The study in [67] shows that wind turbines generate more energy in a year when compared with solar generation of the same capacity. The concept in recent literature combines the technical and economic benefits for optimal RES-DG penetration level assessment. Using techno-economic analysis of a PV-WT hybrid system, ref. [68] claims 32.75% to be the secured penetration level. Ref. [69] reviews the impact of RES-DGs output variation caused by short-time weather changes. The proposed approaches in [70,71] are the steps to developing a more realistic probabilistic model for RES-DG penetration level estimation using solar radiation, wind speed, and panel cost variations. An ideal model will include dynamic RES-DG clusters planning with complex network architecture under systems security constraints.

By considering the impacts of an unconstrained increase in RES-DG penetration into the grid, as discussed in the previous section, it is important to optimally allocate the appropriate RES-DG type. The impact of capacity, types, and operating power factors of different RES-DGs on the grid was investigated in [72]. Analytical approaches based on loss sensitivity factor, voltage stability factor, and selection index for optimal RES-DG allocation are common in recent literature. The approaches are effective and require less time due to the less complex computations involved. The proposed method may be extended to include more power quality and security indices. Focusing on the power quality, a regulator for PV systems' voltage fluctuations and reactive power flow control was proposed in [73,74].

It is also important to consider the steady and rapid load changes during RES-DG penetration planning for different RES-DG types under deterministic annual load growth. Probabilistic methods based on the load shifting technique are considered effective to analyze the network under highly flexible loading conditions. Optimal RES-DG penetration can enhance the system loading factor, line stability, and voltage stability [75]. Table 2 describes the classification of the commonly used optimization objectives for distribution network planning with RES-DG allocation. The optimization objectives are classified as technical, financial, and index-based. Based on the optimization objectives classified in Table 2, the best nodes to allocate RES-DGs within distribution networks can be decided. It is common to combine two or more objectives to form a multi-objective optimization problem for the planning of active distribution networks. For safety-driven power systems, priority is given to the technical and index-based objectives, while financial objectives are considered more important in economy-driven power systems.

Hybrid optimization algorithms may be more suitable for RES-DG allocation particularly for large systems considering the impacts of other network components when a specific performance index needs to be assessed [76]. Hybrid optimization approaches are generally robust in handling the complex mathematical modeling of large unbalanced systems under load and RES-DG output variations. Refs. [53,77] discussed several RES-DG allocation methods with emphasis on the objective functions, constraints, and proposed algorithms. For smaller distribution systems, analytical methods may be effective to obtain the optimal allocation based on simple performance indices. The impact of power exchange at the transmission system-active distribution system (TS-ADS) interface has always been

neglected in the formulation of the problem considering that most RES-DG allocation techniques are focused on isolated systems without interaction beyond the substation. The operation of the emerging grid will be dynamic with flexible services and power exchange at the TS-ADS interface and between multi-voltage meshed networks. This dynamic operation may require optimal reconfiguration of the active distribution system in the future depending on the prevailing condition.

Table 2. Distribution network planning with RES-DG allocation objectives.

Technical Objectives	Financial Objectives	Index-Based Objectives
Specific line and total active, reactive power loss	DG capacity and efficiency maximization	Power loss index
Voltage profile and stability Energy losses	Energy harvest maximization DG costs minimization	Voltage index Current index
Specific line and total power transfer maximization	Profitability, NPV optimization	Short circuit index

4.1.1. Renewable Energy Source-DG Optimal Allocation

Many proposed RES-DG allocation methods have been focused on a single RES-DG type, which may not fully characterize the behavior of a realistic multi-RES DGs system in an integrated grid. The methods are implemented on isolated networks with no comprehensive security assessment index to validate the claims. Consequently, there is a need for more research to develop new objectives and enhanced optimization techniques to dynamically allocate RES-DGs based on peculiar system needs and flexibility supports. Additionally, the tools to implement the new objectives under network security indices should be expandable and adaptable for reliability assessments under dynamic conditions for active distribution network and transmission network interactions. Figure 7 highlights the existing optimization techniques used to allocate RES-DGs to achieve high levels of penetration under prevailing system security constraints. The common metaheuristic algorithms and optimization objectives for RES-DG allocation in recent literature (2010–2020) are summarized in Table 3. While new algorithms such as the Harris hawk optimizer (2019) are being developed, particle swarm optimization algorithm has been applied extensively to obtain the global optima from the fitness/objective functions. Voltage profile enhancement and/or power loss reduction are the most common objective(s) for a single or multi-objective RES-DG allocation optimization problem.

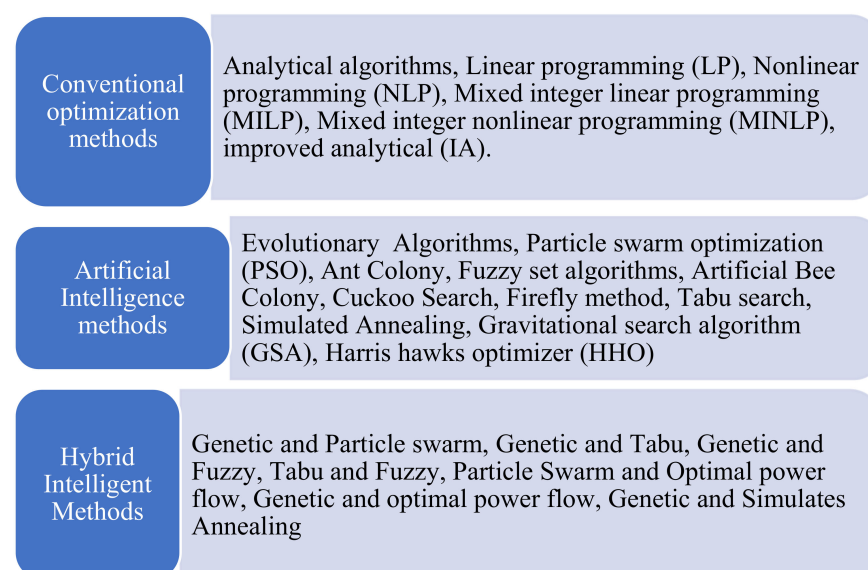| Conventional optimization methods	Analytical algorithms, Linear programming (LP), Nonlinear programming (NLP), Mixed integer linear programming (MILP), Mixed integer nonlinear programming (MINLP), improved analytical (IA).
Artificial Intelligence methods	Evolutionary Algorithms, Particle swarm optimization (PSO), Ant Colony, Fuzzy set algorithms, Artificial Bee Colony, Cuckoo Search, Firefly method, Tabu search, Simulated Annealing, Gravitational search algorithm (GSA), Harris hawks optimizer (HHO)
Hybrid Intelligent Methods	Genetic and Particle swarm, Genetic and Tabu, Genetic and Fuzzy, Tabu and Fuzzy, Particle Swarm and Optimal power flow, Genetic and optimal power flow, Genetic and Simulates Annealing

Figure 7. Optimization algorithm/techniques for RES-DG allocation.

Table 3. Common metaheuristic algorithms with optimization objectives.

Reference(s)	Objective(s)	Method
[55,78–80]	Power loss reduction and voltage enhancement [31]. Power loss reduction [53,55]. Loadability enhancement [54].	Particle swarm optimization (PSO)
[57,81,82]	Power loss reduction and voltage stability improvement [33]. Power loss reduction and voltage enhancement and system stability improvement [56]. Power loss reduction [57].	PSO and GSA [33]. PSO and HHO [56]. PSO and IA [57]
[83,84]	Power loss reduction and reliability improvement [58]. Power loss reduction and voltage enhancement [59].	Sorting genetic algorithm [58]. Genetic algorithm [59]
[85]	Power loss reduction and voltage enhancement	Genetic algorithm with fuzzy logic
[86,87]	Power loss reduction and voltage enhancement [61]. Power loss reduction [62].	Ant lion optimization
[88–90]	Power loss reduction and voltage enhancement [63,65]. Voltage stability improvement [64].	Improved bee algorithm [63]. Artificial bee colony [64]. Improved honey bee mating [65]
[91–93]	Power loss reduction and voltage enhancement [66,68]. Power loss reduction [67].	Differential evolutionary
[94]	Power loss reduction.	Whale optimization algorithm
[95]	Power loss reduction and voltage enhancement.	Dragonfly algorithm

4.1.2. Hosting Capacity Enhancement

The allocation of RES-DG within a network must be as per IEEE 1547.1 standard. This standard provides relevant requirements regarding the distribution network hosting capacity and DGs penetration for secured network operations [96]. The hosting capacity (HC) is defined as the amount of DGs that can penetrate the distribution network while ensuring that the network security constraints are maintained within acceptable ranges without any physical changes in the network topology. The common constraints considered for the estimation of the HC are the thermal, voltage, power quality, and protection constraints [97,98]. The HC concept enables DSOs to quantify the impact of DG units on the performance of the distribution network using a specific set of security indices. Given the global and local constraints, HC values may be assigned to the distribution network and individual node separately. The HC for the node is referred to as locational or nodal HC. Nodal HC is more prevalent for modern distribution networks considering the impact of geographical distance on the voltage constraint, which is one of the major constraints considered in the HC evaluation. The node HC is expressed analytically as the ratio of the power from the DG units to the average load connected to the node.

To accommodate more RES-DGs securely, the HC must be enhanced, as shown in Figure 8. Hosting capacity enhancement may be achieved through distribution network reconfiguration and expansion. With higher nodal HCs, more RES-DGs may be penetrated securely into the active distribution network. Under low nodal HCs and high penetration of RES-DG, the operation of the network will lie within the unacceptable region. Network expansion requires extensive planning, significant investment, and time to implement. Therefore, it is only suitable for long-term HC enhancement. Distribution network reconfiguration is simply achieved by the opening and closing of sectional and tie switches that already exist within the network. Hence, it is suitable for short-term and medium-term HC enhancement.

The distribution network reconfiguration schemes whose primary objective is to reduce the power losses within the network has been extended to enhance the hosting capacities of the distribution network nodes [97,99]. Moreover, to ensure that the security limits are not violated in the occurrence of a contingency, dynamic distribution network reconfiguration methods have been proposed in the literature to redirect power flow throughout the network [100,101]. With dynamic network reconfiguration, the continuity of service across the network zones and areas is ensured. A multi-period optimal power

flow technique with active network management (ANM) architecture for dynamic reconfiguration was proposed in [102]. Under thermal and voltage constraints, the proposed approach attempts to obtain the optimal location that maximizes the penetration size of RES- DGs in the distribution network.
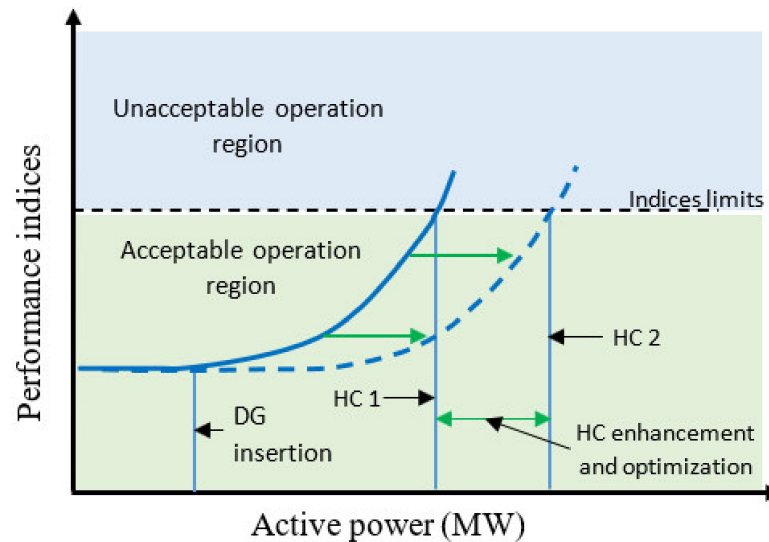

Figure 8. Distribution network hosting capacity.

4.2. Integrated Grid Security Assessment

Methods for system security assessment are broadly categorized into deterministic and probabilistic methods [103]. Under deterministic methods, there must be some pre-existing lists of contingencies and expected responses to be satisfied by the system. Similarly, under probabilistic methods, a secured power system should exhibit a high probability of residing in the secured and alert states under probabilistic network scenarios. A simple and common technique for voltage stability assessment is the continuous power flow (CPF) with distribution-equivalencing-based predictor and corrector with a step length regulator [104]. Grid-wide security state and RES-DGs performance monitoring models are also common techniques in literature [105].

The security assessment is a major concern in the planning, design, and operation stages of electric power systems. This assessment could be carried out under static, transient, and dynamic modes depending on the state of the system, type of contingencies, system parameters, and dynamics focus [106]. The process of detecting the instant state of a power system is referred to as a security assessment. The security of the electric power system with RES-DGs should be tracked constantly using appropriate security indices. Normal state implies that the load is satisfied, and no limit violations occur under prevailing operating constraints and in the presence of unforeseen contingencies. Assessment of these indices may be carried out within a small area network or wide area network. More so, with the likelihood of contingencies, the security tracking process should be adaptable and extended to the alert and emergency states of the system.

The security of the present grid has been challenged due to several technical and economic reasons. Several techniques including analytical methods and heuristic optimization techniques have been applied to solve the optimal load flow problems for the emerging power systems [107,108]. These techniques are aimed at obtaining the best operating states of such networks considering the prevailing constraints. The security of the grid may be easily perturbed under the high penetration of RES-DG into the distribution network due to the characteristics of the generation, future loading, and the network itself. The objectives of a power system include ensuring that the required amount of power is delivered to the customers at an acceptable standard and quality at the normal and alert states of the system. The N-1 and N-2 security criteria are used to evaluate the abilities to operate within

permissible standards at the loss of one and two system elements [109]. This is ensured during the planning, development, and reinforcement of such a network. While the future grid with high RES-DG penetration may present a high degree of adequacy, security is not guaranteed.

The non-linear property of RES-DG power output creates challenges in forecasting and scheduling for system operators. The energy obtained is greater at certain periods and may lead to voltage rises on nodes near the RES-DG site if not promptly curtailed. The impact of excess or surplus power generation from RES-DG systems may be limited through reliable forecasting models considering the prevailing weather factors. A reliable model will include probabilistic load growth and possible network contingencies for dynamic network architectures. Modern transmission network expansion planning (TNEP) has generated concerns about the security and reliability of the emerging grid. These concerns are increased with the proliferation of aggregators into the power trading markets. Most studies have been conducted on the day-ahead market in the planning horizon due to the quantity of energy being traded in this market compared to other markets. The security solution model proposed in [110] is restricted to wind power integration.

To maximize the potentials of active distribution network flexibilities, new models for the integrated grid operation and efficient market structure must be developed. Several articles have been published on the impacts of an active distribution network on the integrated grid with several proposed assessment and enhancement techniques. Ref. [111] presents a review of the impact of flexible resources on the distribution systems in recent literature from the emerging grids' security perspective using three criteria. The criteria include indicators for the security of supply, modeling assumptions made, and flexibility impact assessment methods. The assumptions made for flexibility operations, the trade-off between different flexibility services, and distribution network fault handling are the major assumptions considered.

The intensified investigation of voltage and frequency stability issues is prompted by the challenge posed by high RES-DG penetration. The grid frequency may attain a magnitude outside the statutory range during load demand and supply imbalance. Depending on the distribution network configuration and the RES-DG site, this imbalance may also cause voltage instability [112]. While voltage can be easily controlled at any level within the integrated grid using transformer tap changers and compensators, frequency stability using secondary controls for fast frequency regulation may be difficult to implement considering the several components involved [113]. The importance of transient stability cannot be overemphasized under power system protection. To ensure system security in these conditions, the critical clearing time (CCT) for which each relay would be activated must be predetermined through dynamic stability studies [114]. Existing conventional and non-conventional frequency stability control techniques have been applied to analyze the characteristics of disturbances and to determine the optimal response that ensures the grid's frequency stability. The conventional method includes the primary, secondary, and tertiary frequency response models. The non-conventional frequency control is mostly realized using synchronous and/or non-synchronous DG systems [115].

4.3. Coordination between Transmission and Active Distribution Networks

The interaction between future transmission and active distribution network operators will determine the grid's security in the future. Interaction is required between transmission and active distribution network components that were originally designed to operate independently. The coordination between the components which include the AVRs, FACTS devices, reactors/compensation, tap changers, and virtual power plants will be essential to maintain grid voltage and frequency within and across the transmission and active distribution networks [116]. Distributed coordination of RES-DGs can provide frequency regulation services to relieve the frequency control burden on traditional online automatic governor control (AGC) units. Ref. [117] discusses existing demand-side frequency control techniques for the power grid. The frequency control methods include centralized and

decentralized control for demand flexibility. With demand flexibility, specific residential and industrial loads can be automatically switched off when there is insufficient generation. For the existing control methods to be viable for the future grid, the challenges associated with demand flexibility need to be addressed. One of these challenges is the unpredictable changing diversity of loads, which may lead to more load being switched off than the required amount [118].

The major operation control methods include centralized, hierarchical, decentralized, and distributed control methods [119]. Decentralized and distributed controls are proposed as the preferred control methods for the modern integrated grid in [120]. Optimal ancillary service utilization from the active distribution network through a decentralized control scheme could guarantee a maximum control of the nominal voltage. Under decentralized controls, equilibrium points at which the grids' stability may be guaranteed are discussed in [121]. In modern grid operations, distributed control schemes with exclusively localized algorithms are becoming common [122]. With distributed control, all devices and protocols are distributed, localized, and belong to a unit, while communication is achieved between the local units and control centers. Optimal control decisions can be achieved using key information about the global power imbalance from local frequency deviations on each node. Figure 9 shows the interaction between the TS and DS in an active distributed system for secured future operations. The interaction between the transmission and active distribution networks may be achieved through interaction for inter-network power flow control, network state variables, and flexibility services. The individual network operator manages the assets to achieve optimal power flow control. The system aggregator regulates the allocation and pricing for the normal power flow and flexibility services.
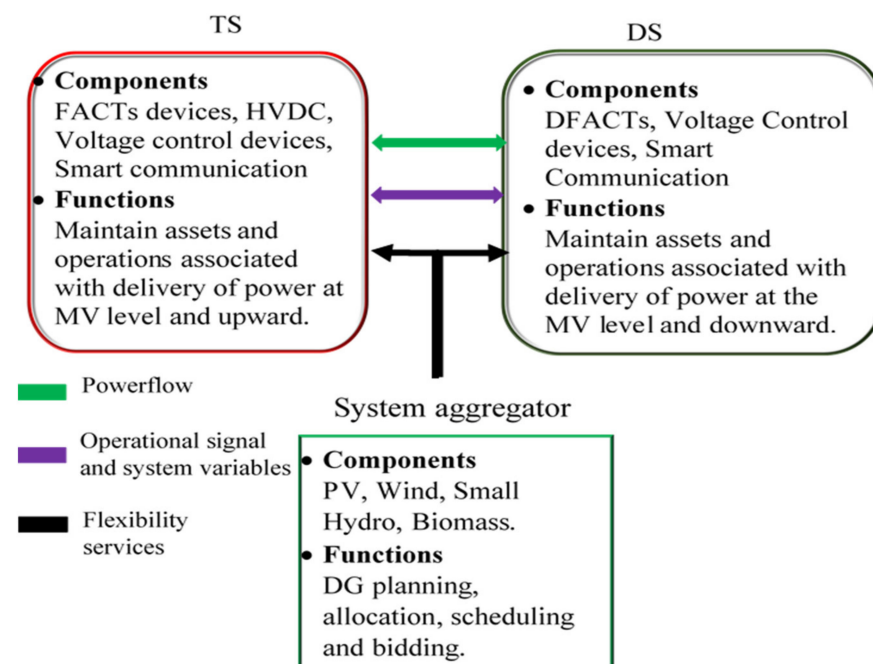

Figure 9. Conceptual interaction between the future TS and DS.

Through coordinated distributed demand-side control with distributed generation for primary frequency regulation, stability may be guaranteed. The objective of good coordination includes achieving fast frequency response through demand response, as demonstrated in [123–125]. The proposed demand response optimal load control technique was improved in [126] by introducing a gain-tuning variable into the multi-objective optimization algorithm.

It is necessary to study the effects of probabilistic and dynamic system loading for efficient generation-load matching. A scheme that consists of continuous fast-acting dis-

tributed load control algorithms for primary frequency regulation implemented at several system nodes can effectively achieve frequency control under dynamic load. A method for the optimal supply and load control for primary frequency stability using the combined passive dynamics of the generation and load scenarios was proposed in [127]. The proposed method can achieve power rebalance and localized frequency resynchronizations with significant improvement in transient conditions.

The impact of generation uncertainty of RES-DGs is critical to the development of flexible market schemes. It is therefore important to study the impact of RES-DG variability on major flexibility services such as energy balancing and congestion management. Enhanced coordination between the TS and DS is important during multiple flexibility services' activation. Integration of the TS and DS flexibility control models for optimal control at the TS-DS interface to achieve global optimization will ensure the secured operation of the grid at high RES-DG penetration levels. Three market designs for TS, DS, and retailers were proposed for flexibility trading in [128]. Flexibility cost estimation and energy sharing were achieved using a series-linked optimization approach in [129,130]. The major drawbacks of the proposed approaches for coordination and optimization are the limits of optimization parameters and system security trade-offs.

Coordinating the voltage and frequency controls for the integrated transmission and active distribution network may be a major challenge in the future grid. The operation of the grid must be within the given voltage and frequency constraints while maintaining the adequacy of the power supply. While it is common to operate the PV and wind turbine systems independently with energy storage systems, a combination of the two systems within a cluster may be predominant in the future to obtain a range of ancillary support. System control, load following, supplement reserve, real power loss replacement, energy imbalance, dynamic scheduling, network stability, and system restoration are some of the ancillary services that will be considered [131]. The efficient operations of RES-DGs clusters depend on the ability of distribution network operators to instantly control the resultant power factor. Ref. [88] discussed several methods for optimal RES-DG types' mix within a cluster to achieve the best responses considering different load types and different load profiles. According to [79], RES-DG types capable of generating both active and reactive power would significantly enhance the grid's loadability and reduce network total losses. Table 4 shows the grid ancillary services from the RES-DG types and battery storage.

Table 4. Renewable energy resource and energy storage system ancillary services.

Ancillary Service	Solar PV	Wind Turbine	Hydro	Battery Storage
Reactive and Voltage Support	***	***	***	***
Frequency Regulation (steady-state)	**	**	***	***
Frequency Arrest (transient state)	**	**	**	**
Frequency Support (Rebound Period)	**	**	***	**
Frequency Support (Recovery Period)	**	**	***	**
Dispatchability/Flexibility	*	*	***	***

Good *, Very good **, Excellent ***.

5. Research Trends for High RES-DG Penetration Support

5.1. Supporting Technologies

This section discusses the recent smart technology devices and concepts that support the penetration of RES-DG into the grids. A growing concept among scholars is the idea of an AC-DC nanogrid, which is suggested to become the basic building block of the future grid. This idea is directed toward the residential networks at the lowest power and voltage levels. Although the idea may imply a purely off-grid RES-DG system, the advantages of the nanogrid include fewer power converters, higher overall system efficiency, and easier interfacing between DC supply and DC load. Additionally, there is no frequency stability and reactive power issues, and the power losses are very minimal [132]. The nanogrid model will be supported through advancements in small-capacity energy storage

systems (SCESS), high-temperature superconducting (HTS) materials, and smart home energy management systems (SHEMS).

5.1.1. Energy Storage Systems

In the future, storage systems will be more enhanced and easily handled, using predominantly modular power flow technologies. Supercapacitors, batteries, and magnetic energy storage will be readily available and easily accessible. Consumers will have access to storage devices with high power and energy densities at efficiencies over 90% [133]. Table 5 shows the characteristics of available energy storage devices.

Table 5. Energy storage types and characteristics.

ES Systems	Power Rating (MW)/Unit	Energy Density Wh/L	Power Density Wh/L	Response Time	Discharge Time	Efficiency (%)
Pumped Hydro	100–2500	0.2–2	0.1–0.2	10 s–12 min	4–16 h	70–85
CAES	100–1000	2–6	0.2–0.6	12 min	2–30 h	79–90
BESS	0.001–100	150–300	120–160	seconds	1 min–8 hrs	80–90
Flywheel	0.005–20	20–80	5000	seconds	sec-min	80–95
SMES	0.01–100	~6	~2600	milliseconds	millisec-seconds	80–95
Super Cap	0.01–1	10–20	40–120,000	milliseconds	millisec-min	80–95

Availability of high-capacity energy storage systems will mitigate the technical issues caused by variabilities of the RES-DG output in a high penetrated distribution system. The energy storage systems will also support power generation during transient and sustained load spikes resulting from electric vehicles. Recently, energy storage systems and mobile distributed generation systems have been utilized as virtual power plants (VPP) and inertia emulators for grids' voltage and frequency support. The impact of electric vehicle (EV) loads on the grid must also be considered during active distribution network planning. The models for EV load forecast should be developed for real-life charging scenarios (home, office, and trip) and drivers' schedules (work, leisure, and shopping). Future models will consider from long-term to inter-hour EV load forecasting to achieve the minimum distribution network load-generation imbalance. To obtain reliable energy management models, the models should be extended beyond the common EV parameters such as arrivals and departure time, state of charge (SOC) at the beginning and end of the trip to include location, and specific EV user behaviors, which may only be stochastically modeled.

5.1.2. Communication and Data Security

The grid is designed to operate in a hierarchical operational structure consisting of several layers. The five common layers to most power grids are the control application, network services, network measuring and monitoring, physical, and communication layers. These layers are embedded and coordinated to ensure the continued grid operability [134]. An enhanced real-time grid-wide monitoring system has been proposed to monitor the security of the grid. The application of a real-time monitoring system can be extended to the distribution network with synchro phasors on nodes with RES-DGs to monitor generation output and local demand fluctuations. The smart communication system is also essential for the coordinated operations of CGs and DGs protection systems, tracking of disturbance for quick islanding action, and resynchronization functions [135]. The wide-area monitoring analysis protection-control system (WARMAP) is one of the existing systems designed to ensure the safe operation of the integrated transmission and active distribution networks across these layers [136]. The communication layer, which is the key to the emerging grid operation, is equally critical to the WARMAP system. The communication layer describes the information exchange among actors in the different layers according to the services to be managed and provided for both long-term and short-term operational services. Communication interruption, as a result of high channel latency, reduces the reliability of existing security monitoring systems [137]. To prevent the

breakdown between the layers, it is necessary to review and regularize the information communication systems standards, codes, and requirements.

The communication layer is also important to the realization of the energy internet through the possibility of grid components to operate in the plug-and-play model. Although the implementation of energy internet will improve the system reliability and energy efficiency [138], several concerns must be considered. Some of these concerns include challenges in component standardization, stability issues, cyber-attack vulnerability, and scalability [139]. Consequently, the goal of recent research in the area of energy internet has been focused on addressing these concerns [140]. Smart sensing systems and remote IoT devices have been developed to monitor energy flows at the system nodes. These devices will have the capability to automatically re-route power based on the programmed criterion for optimal operation of the grid [141]. Several architectures including the Future Renewable Electric Energy Delivery and Management (FREEDM) in the USA and Global Energy Interconnection Development and Cooperation Organization (GEIDCO) in China have been implemented to achieve the vision of the energy internet through the integration of RES-DGs with standardized plug-and-play interfaces [142].

A review of smart grid communication technologies was presented in [143] focusing on the use of power line communication (PLC). It was concluded that PLCs with medium access control (MAC) and time domain multiple access (TDMA) protocols are effective for smart grid communication due to their flexibility. However, their applicability for real-time operation monitoring between the transmission and active distribution operators is uncertain due to their low coexistence efficiencies. Ref. [144] demonstrated that the frequency stability of the emerging power system may be enhanced through the utilization of the appropriate data communication topology for RES-DG control to achieve fast secondary frequency response. Data transferred through the PLC can be used for effective voltage control by the transmission system operators. Data nodes, which are referred to as control agents, are installed on the transmission system nodes to stores the voltage states of the nodes. In [145], the control agents were employed to make operational decisions by optimizing the present and future voltage state within the network constraints.

The integrity of transients and RMS network data transfer is crucial to the protection systems. A backup protection scheme for traditional protection using fast data exchange approach for interfaced islanded RES-DGs is demonstrated in [146]. The IEC 61,850 standard emphasizes the importance of integration and unification of communication standards between different network components and models. Ref. [147] achieved the interfacing of the distributed energy sources' testbed in the smart grid energy research center (SMERC) from the USA with the Korean institute of energy research (KIER) testbed. The interface aims to develop a communication-supported microgrid digital protection relay for fast fault detection across the two testbeds. The method involves the application of a distributed microgrid digital protection relay, which communicates with the microgrid central protection manager (MCPM).

The ability to accurately model active distribution systems with smart grid components and associated characteristics will require existing tools to significantly adapt to meet the new conditions. Enhanced and faster computing methods will be key for tool development in active distribution system analysis to support the emerging grid. The integrity of system data and information is crucial to the operation of the emerging grid. Despite its many advantages, the emerging grid is characterized by various security attacks since it combines several components. Some of these components, which include synchrophasors, the internet of things (IoT), wireless devices, and industrial components, are susceptible to a variety of attacks. Device attacks, data attacks, privacy attacks, and network availability attacks are some of the existing and potential attacks. Furthermore, the existing technologies for protection against these attacks have not integrated modern security solutions; therefore, may not be effective [148]. The capacity to sense and prevent an attack at different network layers and levels under dynamic system architecture through advanced information security devices is critical to the grid's security. The consideration

of these attacks increases the complexity of planning and grid restoration models for the emerging grid [149].

5.2. RES-DG Penetration Level

Renewable energy sources DG penetration increases the scope and complexity of active distribution network planning and operation due to the variables that are considered. Attempts to define RES-DG penetration have been about the space utilization for PV and WT installation to the total space, the annual energy from DG systems, and the total energy consumption relative to the transformer capacity. More specifically, RES-DG penetration can be defined as the ratio of the total RES-DG power to the peak load demand on a specific feeder in a distribution network [150]. It is indeed necessary to make reasonable assumptions to develop a feasible RES-DG penetration modeling considering several parameters involved. The parameters include the number and types of clustered RES-DG connected to a point, the power factors of the DGs, physical upgrades and investments on network elements, and the variations of wind and solar irradiance. These parameters will be combined and optimized to obtain several best operation stochastic scenarios for a specific active distribution network at specific times. To optimize the operating state of a network, the approaches proposed by scholars can be categorized into the distribution power flow approach, scenario-based approach, engineering approach, and network planning approach.

The maximum allowable RES-DG penetration can be determined by constantly observing the networks' security limits as the penetration is steadily increased. Many traditional rules and guidelines including the rule of thumb will no longer be applicable. New guidelines and techniques, therefore, need to be developed. According to the general principle, a RES-DG can be penetrated up to 15% without having any significant technical impact on the distribution system [151]. This is while the zero-point analysis focuses on the point on the feeder where power flow is zero due to the RES-DG unit aggregated output. The secured increase in the RES-DG penetration lies in the capabilities of the grid-following inverters to support frequency and voltage using local distributed and decentralized frequency and voltage regulation strategies.

Operating a zero-inertia system with grid-following inverters, where it is unclear which grid components are responsible for frequency and voltage regulations in an emergency state, is at the moment hypothetical. The future power grid models a system with a very low inertia requirement since many synchronous generators will be replaced with non-synchronous generators. This model may be feasible with the guarantee of only small and steady power imbalances. However, to ensure the security of the emerging grid during fault conditions, a significant level of inertia proportional to the capacity of the grid is required. While the possibility of a 100% renewable energy grid was discussed for small and large power systems in [152], a safe RES-DG penetration level of 20–30% for the grid security to be guaranteed was recommended in [153]. This secure penetration level is recommended given that traditional frequency control methods may not be suitable for the integrated transmission and active distribution network operation under normal and contingency conditions. To this end, new tools to dynamically assess the safe RES-DG penetration level into the distribution network for secure operation under normal and N-1 states considering changing network architecture are needed.

The allocation of RES-DG is dependent on the structure and load concentration of the distribution network. Allocation of RES-DG simply means to determine the size of the RES-DG and the siting of the RES-DGs within the distribution network. The size of the RES-DGs is determined from the distribution network feeders' hosting capacity [97]. The hosting capacity is used to describe the RES-DG penetration level below which the grid is secured without network reconfiguration or reinforcements. Since the hosting capacity of the node reduces with distance from the substation, reconfiguration of the distribution network is useful to ensure high hosting capacities at certain network nodes [154]. The future active distribution networks will be highly meshed to obtain higher feeders' hosting

capacities. However, solutions to the difficulties of operation of the protection devices need to be developed. Since the relation between the maximum penetration of clustered RES-DGs and the distance from the TS-DS substation has been established, the objectives of allocation techniques and methods include determining the level of generation scheduled to these RES-DGs considering security constraints.

5.3. Integrated Transmission-Active Distribution Security

The discussions on emerging grid security have been focused on the impact of high RES-DG penetrations on the transient stability of the grid [155]. An attempt was made in [156] to include probabilistic characteristics of wind DG into the grid's oscillatory stability margin (OSM) using random modeling and quantitative statistical analysis. It was claimed that the location and existence of high wind DG penetration are detrimental to the OSM of the active distribution network. Enhanced real-time system monitoring can be achieved with phasor measurement units (PMUs) combined with artificial intelligence-based state estimation during normal and contingency states. A heuristic technique-based quantitative assessment of dynamic and transient stability using PMU and wide-area monitoring (WAM) techniques to analyze various stability concerns in the smart power grid caused by DG was proposed in [157].

The optimal distributed power flow control within the emerging grid will depend on reliable network component modeling. The modeling and assessment of the impacts of RES-DG on the emerging grid are mostly stochastic due to the generation and load variabilities. However, to develop functional and reliable models, some degree of certainty will be assumed. New techniques that combine deterministic and probabilistic methods have been developed in recent literature. A hybrid method was proposed in [158] to study the impact of PV-based DG units on the distribution system. The impact of wind generation uncertainties on the generation and transmission expansion planning was also studied in [159] using hybrid quantitative and heuristic modeling.

Models for efficient bidirectional power flow control between the transmission networks and active distribution networks are important to ensure the reliability of the protection systems. Two hierarchy levels of optimal power flow were proposed in [160] to achieve decentralized optimal operation between the TS and DS. While many deterministic or probabilistic techniques have been proposed in the literature for the security assessment of grid with RES-DG, few considered the N-1 and N-2 security criteria for a given system operating state. Developing deterministic security assessment methods for the grid is straightforward and also easy to implement. However, generalizing the results of the worst-case scenarios obtained using such a deterministic model may not fully represent the response of the network during contingencies. Few other papers considered probabilistic approaches for reliability assessment using indices such as the Loss of Load Probability (LOLP) and Loss of Load Frequency (LOLF) to evaluate security under steady and transient states. However, to deal with the frequently occurring RES-DG and EV variations, as well as occasional network contingencies, such a security assessment approach requires extensive computation and simulation. Hence, the security of the emerging grid may be ensured using dynamic security assessment tools for the integrated grid considering several deterministic and probabilistic conditions in the transmission network, active distribution network, and the TS/DS interface.

6. Conclusions and Future Work

6.1. Conclusions

High penetration of RES-DG into the distribution networks creates many operational benefits as well as some technical concerns. The flexibilities of DG systems will increase grid resilience and enhance grid stability through ancillary services support if properly planned and operated. The latest trends for the emerging grid operation, framework, components, tools, and techniques were discussed in this paper. Renewable energy sources DG penetration allocation using various techniques, which include analytical, conventional,

and AI-based optimization methods, were reviewed. Technical impacts of high RES-DG penetration on the distribution systems were investigated using various indices (power losses, voltage, and transient stability index) under various deterministic and probabilistic approaches. Reliable tools for RES-DG clusters generation schedule may be achieved through enhanced prediction models for RES-DG generation forecast considering short time planning, weather conditions, load forecast, and network constraints.

Conventional relays are unreliable for system protection due to variations in the direction and level of fault currents. Excess current is generated during the off-peak demand period and peak generation period from RES-DG causing unintended reverse power flow. The protection system selectivity is impacted by the reverse power flow, thereby, occasionally resulting in false tripping. Advancements in alternative protection systems such as directional overcurrent relays will improve the coordination of protection devices within the grid under high RES-DG penetration.

This review showed that the present grid relies on the independent frequency and voltage controls within the transmission and active distribution systems using central and hierarchical approaches. In conclusion, the major limiting factors for high RES-DG are voltage instability issues, protection challenges, and reduced resultant system inertia. The proposed techniques for voltage control and new protection schemes in the literature are promising to be considered for practical applications. However, until synthetic and virtual inertia emulation systems, as well as upgraded energy storage systems, are fully deployed in the TS and DS, the question of how much RES-DG penetration into the active distribution system is safe remains unresolved to a considerable extent.

6.2. Recommendations for Future Research

This paper presented a discussion about the emerging grid framework and the technical issues regarding its security. Various tools and techniques proposed to assess the impact of high penetration of RES-DG into the grid were also reviewed. Observations were made concerning the limitations of the proposed approaches aimed at ensuring the security of the emerging grid with high penetration of RES-DGs. Following these reviews and conclusions, more research to address limitations in these areas is needed:

- Dynamic and adaptable RES-DG clusters allocation technique considering system ancillary services.
- Security assessment of integrated TS-DS considering active distribution network architecture reconfiguration scenarios.
- Enhanced interaction and coordination for voltage and frequency control schemes in an integrated TS-DS with demand-side management.

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