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Voltage Rise Problem in Distribution Networks with Distributed Generation: A Review of Technologies, Impact and Mitigation Approaches

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ABSTRACT

Energy demand has constantly been on the rise due to aggressive industrialization and civilization. This rise in energy demand results in the massive penetration of distributed generation (DG) in the distribution network (DN) which has been a holistic approach to enhance the capacity of distribution networks. However, this has led to a number of issues in the low voltage network, one of which is the voltage rise problem. This happens when generation exceeds demand thereby causing reverse power flow and consequently leading to overvoltage. A number of methods have been discussed in the literature to overcome this challenge ranging from network augmentation to active management of the distribution networks. This paper discusses the issue of voltage rise problem and its impact on distribution networks with high amounts of distributed energy resources (DERs). It presents different DG technologies such as those based on conventional and unconventional resources and other DERs such as battery storage systems and fuel cells. The study provides a comprehensive overview of approaches employed to curtail the issue of voltage increase at the point of common coupling (PCC), which includes strategies based on the network reinforcement methodology and the active distribution network management. A techno-economic comparison is then introduced in the paper to ascertain the similarities and dissimilarities of different mitigation approaches based on the technology involved, ease of deployment, cost implication, and their pros and cons. The paper provides insights into directions for future research in mitigating the impact of voltage rise presented by grid-connected DGs without limiting their increased penetration in the existing power grid.

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1. INTRODUCTION

Political drives to solve the problems of climate change and air pollution as well as the technological advances being made in Distributed Energy Resource (DER) technology have led to the rapid integration of distributed generation (DG) on the distribution networks (DNs) [1, 2]. DG may be described as a kind of power generation that is of relatively small capacity (up to 50MW), which is interconnected at the substation, distribution feeder, or customer load levels with the vast majority coming from renewable sources [3, 4].

Traditionally, DNs are meant to be passive and built to supply customers with a reasonably constant voltage. This implies that they are designed to allow power flow from the large central generation, down to the LV consumers with the assumption that no generation will be connected to the distribution system or customer loads [1, 5]. Connection of DG, in the form of an embedded generator (EG) to the existing network, therefore, invalidates these norms as the conventional unidirectional power flow is being altered from the high to low voltage sections and levels of the electrical system [6]

The impact of DG on the distribution network can sometimes be beneficial to the system especially when the generated power matches the consumer load. Such advantages are generally referred to as “system support benefits” and they help to minimize losses and manage the network demand [7]. When there is a high injection of DG power, the architecture of the distribution network is being challenged and the impact can limit the allowable DG capacity on the network. The impact includes the: steady-state voltage rise, bi-directional power flow, exceeding thermal limits, voltage flicker, increase in short-circuit levels, and protection degradation [5, 7, 8, 9]. These impacts have been investigated and analyzed by some existing studies [3, 8, 10, 12-14]. The steady-state voltage rise has been identified as one having a dominant impact of the DG on the DN [15], which occurs when power generation goes beyond the local demand, thereby, leading to the challenge of keeping the voltage within statutory limits.

It is necessary to state that voltage increase as a result of low penetration of DG may not constitute a problem if it does not exceed the allowable value of voltage rise, i.e. the set limit, at the PCC. This is because the cluster of DG systems is accommodated into the network without any stress. However, the set limit is usually exceeded when a high proportion of DG systems is integrated, which can lead to overvoltage. This is due to the interaction and cumulative impact of multiple generators. The unhealthy effect of overvoltage and other issues such as bi-directional power flow, power quality distortion, instability, etc., in the network, requires the use of effective mitigation and control strategies when integrating a high percentage of DG technologies with the existing grid. The size, fuel type, location, and reliability of DG are some of the crucial factors that need to be considered for planning and development purposes. Besides, some standards are also required for control, installation, and placements of DG to minimize the impact of deploying a significant amount of DG on the network [1, 3].

The effective integration of DG systems into DN requires that an optimal sizing and location of the technologies must be considered to avoid power losses while ensuring an acceptable voltage profile and forestalling harmonic distortion. To that effect, several woks of literature have employed various methods like the genetic algorithm (GA), the particle swarm optimization algorithm (PSO), and the artificial bee colony algorithm (ABC) for sizing and placements of DG [16]. For instance, a study has considered the techno-economic analysis of DG optimal location and sizing based on a multi-objective particle swarm optimization (MOPSO) [17]. The idea presented in this paper is to ensure an optimal capacity and location of the DG in relation in the existing DN.

The distribution network operators (DNO) usually put a conservative limit on the DG capacity that can be connected to the existing network. This is done to forestall a voltage violation by restricting DG units from generating when the network voltage is close to the statutory limit [1, 11]. However, limiting the power generated by DGs reduces the efficiency and prevents full exploitation of the benefits presented by the DG sources, especially the eco-friendly resources such as solar PV, wind, biomass, water, etc.

The distribution networks have in recent years' experience the incorporation of different distributed generation technologies that can be classified as fossil fuel-based and renewable energy-based systems. The fossil fuel systems include the combustion engines – reciprocating and Stirling engines and the microturbines, while the renewable energy-based systems include wind turbines, solar PV arrays, and the small hydro plants (SHP) [18, 19]. These technologies can also be interconnected to form a microgrid that is currently evolving as a result of numerous advantages it offers [20], and they vary in terms of capabilities and performance, and can also impact DN differently because of their different features and characteristics [21]. Hence, the need to appropriately select a suitable technology to deploy when the need arises.

Several studies exist in the literature that considered the integration of DG units into the distribution power network. The voltage rise problem in a low-voltage network characterized by residential photovoltaic (PV) systems and electric vehicles (EVs) has been discussed [22]. The scholarly work employed a rule-based control method and a three-phase optimal power flow-based control method to control on-load tap changer fitted transformers. The authors showed that the employed method has the capability to provide practical solutions. An approach for the optimal capacity of PV inverter has been presented to mitigate the voltage rise in DN [23]. The IEEE 119-node distribution network was adopted for testing the proposed approach, and results revealed that the voltage regulation problem resulting from the grid-integrated PV was resolved.

A study has also examined the impact of integrating combined heat and power (CHP) and wind power generation systems with the DN [24]. The authors considered how the voltage profile has been affected by DG technologies. The ERAC power flow analysis software was used to validate the proposed model on a seven busbars DN, which mimics a real network with DG units connected at a voltage level of 38 kV. The optimal sizing and location of a wind generator in the distribution network have been discussed with emphasis on real power loss minimization using an analytical approach [25]. The author considered a radial distribution network, which was modeled with the assumption that the wind generator is installed one at a time without considering the economic aspect of the system. The approach was tested for effectiveness using the 33 and 69-bus systems in terms of the voltage profile and the branch currents. The sizing and control strategy of a hybrid stand-alone PV/wind generator has been presented using a differential flatness approach [26].

DGs are capable of injecting both reactive and active power in the DNs depending on their types. While some DG injects reactive power, others inject active power. Therefore, care must be taken to ensure that the DG to be incorporated in DN injects the type of power needed in the DN [27]. A reactive power compensation-based voltage profile regulation of DN with DG has been presented [28]. The worst-case scenario static analysis of a 15-bus Kumumoto system has been considered by the authors with an emphasis on photovoltaics, synchronous, and wind generators. Similarly, a multi-agent system (MAS) has been employed for the reactive power control of DN with DG to manage and regulate the voltage profile. The MAS was tested on an IEEE 33-bus system and the sensitivity analysis of the system reveals that the proposed strategy is effective in mitigating voltage problems [29]. Besides, a random gradient-free algorithm was employed by [30] to optimize the reactive power of DN with DG. The interaction between the capacitor banks and the DG units was used by the algorithm to obtain the global optimum solution. The model was then tested on a modified IEEE-69 bus system and results revealed its capability to regulate the voltage profile of the network. A system for compensating both active and reactive power has been discussed, which is based on Biogeography Based Optimization (BBO) technique in a DN with DG [31].

The existing knowledge has shown that DGs can generally be operated in either constant voltage (PV) or constant power (PQ) modes and the mode of operation can impact the voltage profile of DNs [32]. An evaluation of the impact of the modes of operation of DG units on DN has been investigated by [33]. The authors employed the voltage stability index (VSI) and the active power voltage stability index (P-VSI) to examine the performance of the system. The study demonstrated that there is a reduction in power losses and improvement in the voltage profile when the DG is running in the PV mode. A comparison of the operation modes of DG in terms of voltage profile and system stability has been studied on the IEEE 33-bus radial distribution system [34]. The work showed that operating a DG system in the PV mode is more beneficial in terms of reduction in power losses and enhancement of voltage profile than PQ mode.

The mentioned papers have presented contributions in different aspects of integration issues of DG technologies. The studies do not only discuss the ancillary support roles of integrating DG systems with the DN but also presented the associated challenges when such technologies are introduced to the existing network that is designed to permit a one-way power flow. The contributions are a relevant background to the aspect that is presented in this current paper. Therefore, this paper takes a different dimension by considering the issue of voltage rise problem and its impact on distribution networks with high amounts of DG systems. It discusses different DG technologies such as those based on conventional and unconventional resources, and other DERs such as battery storage systems and fuel cells. The study provides a comprehensive overview of approaches employed to curtail the issue of voltage increase at the PCC and in the surrounding section of the network, which includes strategies based on the network reinforcement methodology and the active distribution network management.

A techno-economic comparison approach is then introduced in the paper to ascertain the similarities and dissimilarities of different mitigation approaches based on the technology involved, ease of deployment, cost implication, and their pros and cons. This is achieved by presenting an in-depth discussion and analysis of the existing technical methods available in the literature and the emerging strategies for mitigating the issue of voltage rise in the LV distribution network. The paper also suggested possible directions for future research. The relevance of the paper is that it provides insights into directions for future research in mitigating the impact of voltage rise presented by grid-connected DG technologies without limiting their widespread application and increased penetration in the existing power grid.

The remaining part of the paper is arranged as follows: section 2 discusses DG technologies and voltage rise impact, section 3 presents the methods to curtail voltage rise effects, section 4 discusses cooperative voltage control strategies and a techno-economic comparison of the mitigation strategies, section 5 presents recent trends in addressing the issues associated with grid-connected DG and the future research directions while section 6 concludes the paper.

2. DG TECHNOLOGIES AND VOLTAGE RISE IMPACT

DGs generally may be powered by either conventional or unconventional energy systems. While those that are based on conventional energy resources make use of diesel or petrol generating, Stirling engines, natural gas-based microturbines technologies, the unconventional systems are mostly based on the eco-friendly systems such as solar photovoltaic, wind, biomass, small hydro, and fuel-less power generation technologies [35, 36, 37].

Apart from these resources, other important distributed energy resources (DERs) that are employed for ancillary service in grid-integrated systems are battery storage and fuel cell systems [38-40]. Detailed energy storage options and applications have been reported in the literature [41-43]; however, the grid-integrated application of battery storage systems is of interest in this paper in light of the voltage rise issue of high penetration of DGs.

The major differences between a DG and a conventional power generation system include the fact that distributed generators have a smaller power capacity compared to the large generators that are operated in conventional power production systems, the electrical power produced at distribution voltage level could be integrated with the existing DN, and DG systems are usually in proximity to the end-users' premises for quality and efficient supply [44].

2.1 DGs Based on Conventional Resources

2.1.1 Reciprocating Internal Combustion Engines

This DG system makes use of the reciprocating system, which is regarded as internal combustion engines (ICEs) driven by a piston and connected to fixed-speed ac generators [4]. Such a power generating system has an efficiency of ~0.4 on the lower heating value (LHV) basis with capacities from 0.5 to 6500 *kW*. Reciprocating systems may be fueled by gasoline, natural gas, kerosene, propane, H_2, fuel oil, alcohol, and waste-treatment plant digester gas [4]. They have a low cost compared to other DG systems with less environmental impact when they are fueled by natural gas resources, and they also find applications in cogeneration systems [4, 45 - 48].

Most of these engine systems operate on a 4-stroke cycle, which is similar to the engines in automobiles and trucks [4]. The cycles include the in-take stroke, compression stroke, power stroke, and exhaust stroke. The Otto-cycle and the Diesel-cycle are two variants of the 4-stroke engine design. They are also regarded as the spark-ignited (s-i) and the compression-ignition (c-i) systems, respectively. Gasoline or fuel like the natural gas that can be easily ignited is used to run the s-i engines, while diesel or fuel oil are used to operate the c-i engine systems.

2.1.2 Stirling Engines

The s-i and diesel reciprocating engines are two forms of ICEs [4]. This implies that combustion occurs inside the engine, while an alternative mode is through the external combustion using the Stirling engines, whereby energy is provided for the working fluid from outside the engine. This is why the Stirling engines are referred to as external combustion engines (ECEs) such as a steam cycle power plant. ECEs can be operated on any fuel or high-temperature sources like concentrated solar.

The Stirling engines also provide the benefit of cogeneration applications, but they generate emissions when they run on fossil fuel and could be affected by changes in fuel price. It is on this basis that an eco-friendly fuel such as concentrated solar is sought to minimize the environmental impact. Another inherent feature of the ECEs is that they have a quiet operation because they burn the fuel slowly and steadily devoid of explosions. Their capacities can be up to 25 *kW* but they have a relatively low efficiency of < 0.3 [4].

2.1.3 Microturbines

These are small gas turbines with sizes ranging from around 0.5 *kW* to hundreds of *kW* capacity [4]. A basic design of microturbines (mTs) is such that includes the compressor, turbine, and permanent-magnet (PM) generator, which are configured or mounted on a single shaft. The air that is fed into the system is compressed and passed to the recuperator – a heat exchanger component so that its temperature may be increased through the hot exhaust gases [49]. The compression is achieved by raising the pressure to 3 to 4 atmospheres [4]. The air, after being compressed and heated, is combined with fuel in the combustion chamber which is then burned. The hot gases expand through the turbine, which turns the compressor and generator.

There are several specifications of mTs designs, one of which is the one manufactured by the Capstone Turbine Corporation that can produce up to 60 *kW*, and that of the Elliott 100 *kW* system that is capable of delivering up to 105 *kW* electrical power including 172 *kW* of heat [4]. The turbines manufactured by the Capstone Turbine Corporation, for example, are configured with only "one moving" part just as mentioned earlier, which implies that the common shaft combines the compressor, turbine, and generator, with a rotation up to 96×10^3 *r.p.m*. Another unique characteristic of such machines is that the shaft rotation is achieved on air bearings without any requirement for lubrication and there no gearboxes and coolants, which translate to relatively low maintenance. They also generate relatively low emissions [47, 50].

The development of heat energy in mTs is also an advantage for combined heat and power applications [49-51]. A network of mTs may be a potential source of electrical power generation for grid-independent applications. This means that the mTs could be integrated to develop modular packages with capacities of more than 1MW [47]. Such arrangements may also be integrated with the existing distribution network in which case the machines will be synchronized with the grid.

2.2 DGs Based on Unconventional Resources

The unconventional energy resources are essentially renewable energy technologies such as solar, wind, biomass, tidal, small hydro, etc. One of the features of this class of energy resources is that they have a variable characteristic, which is of interest and significance in their utilization and application. The integration of such resources usually challenges the architecture of the existing grid and has evolved the application of other technologies such as battery and power electronic converters.

2.2.1 Solar

A DG system may also be fueled by solar energy resources [52-54]. In this case, either the solar photovoltaic module or the solar concentrated technology is employed for harnessing the energy from the sun depending on the application involved. In other words, solar energy technology in distributed generation application is classified into the solar photovoltaic and solar thermal systems [55, 56]. In a typical off-grid situation, battery storage is required because of the intermittent characteristics of the solar energy resource. However, battery storage may not be used in certain grid-connected applications, e.g., household systems [36]. The inverter is required for the on-grid and off-grid applications since it is necessary to convert the DC output of the PV to AC for the appliances and the grid.

Several studies have been reported in the literature that is aimed at advancing research and development in the aspect of distributed solar photovoltaic systems. For instance, a recent study has considered the trends and challenges of grid-integrated solar photovoltaic systems [57]. The authors present a review of the recent developments in the aspect of on-grid solar photovoltaic systems. They mentioned the challenge of high penetration of DGs as potential source of pressure on the existing DNs, and then presented some existing methods of addressing the technical challenges associated with increased deployments of on-grid solar PV systems. The paper also discussed the application of the Maximum Power Point Tracking (MPPT), Solar Tracking (ST), and the transformer-less DC-AC converters as means to realize efficient energy capture in PV systems with minimal “interference” or impact on the existing distribution grid. Also, it adds that DC- AC power converters that are employed for ancillary services are important for mitigating the effect of a high proportion of on-grid photovoltaic systems.

Another study discussed the mitigation of rooftop solar photovoltaic impacts [58]. The authors also presented evening peak support through the management of the available distributed energy storage systems. The authors first recognized that a high proportion of rooftop distributed solar PV into LV DNs leads to reverse power flow and voltage increase problems. One way to dissect this problem is when the distributed solar generation exceeds the load demand when there is high solar irradiation. The paper discussed the integration of distributed energy storage systems with solar PV generation in LV networks so that the surplus energy may be stored and then used during peak periods, including evenings. It also presented the charge/discharge control mechanism for the battery energy system based on the state of charge, depth of discharge, and the length of charging time.

The power quality evaluation of grid-integrated solar photovoltaic power generators has been discussed, using Brazil as a test case [59]. The authors began by positing that a typical DN has a “passive” characteristic with respect to power flows, implying that the traditional DN allows unidirectional flow of power from DN substation to loads via the feeder. However, the integration of solar PV generators with the DN alters this design, the behavior, and the characteristics of the grid, which may affect the power quality of the electric power.

2.2.2 Wind

Wind-based DG systems are those electricity generation systems fueled by the wind energy resource [60]. Like every other renewable energy resource, the wind energy also has intermittent characteristics, which justifies the use of energy storage systems with them to store energy during windy periods which may not even coincide with the peak periods [61]. Several studies have reported the integration of distributed wind power in different parts of the world. A study presented wind power integration, which discussed the opportunities and problems that are associated with on-grid distributed wind power in DNs [62]. A review has been published on the integration of renewable distributed generators into the DNs [63]. The authors presented the technical benefits and the operational issues of integrating distributed renewable energy technologies, such as solar, wind, etc., with the existing power grid.

Besides, the technical issues of wind power integration have been presented, with emphasis on the effects of wind power on the power system, the power system operating cost, power quality, power imbalances, power system dynamics, and impacts on transmission planning [64]. Another study has considered wind energy systems where the authors identified some emerging challenges that still need attention. This study presented an overview and some trends in the power electronic converters utilized for wind power production., while the technical issues and actual solutions of grid-integrated wind energy systems have also been discussed [65].

2.2.3 Biomass

DG systems may also be fueled by biomass resources [66]. Apart from power generation through thermal means, where steam is being raised to operate a turbine and then spin an alternator, the distributed biomass power system also has the benefit of making use of the waste heat, i.e. combined heat and power [67]. Several research studies have been presented in the aspect of distributed biomass systems. For instance, an existing paper focuses on the design and optimization of biomass power plants [68]. The authors mentioned the challenge of moisture in biomass that lowers the calorific content of the resource, reduces the temperature of combustion leading to operational challenges. This problem has traditionally led to the drying of the biomass in the combustor before it is processed or burned for electricity production. The authors introduced a multi-stage drying process that utilizes steam and waste-heat from the biomass plant and the drying process, respectively This has the capability to improve the efficiency of the biomass power system.

Another research work has considered the experimental analysis of integrated biomass gasification and power generation system with an emphasis on distributed power system applications [69]. An emerging trend in biomass technology is the hybrid system, and a recent study focuses on the Power-to gas-biomass oxy-combustion hybrid system [70], where the authors considered the aspect of energy integration and applications. In this paper, the authors evaluated the efficiency of an energy integrated system under different capacities and applications.

2.2.4 Small Hydro

The centralized hydropower technology is widely recognized around the world as a mature and viable system for power generation. However, a distributed generation system is possible through a small hydro resource. A study has discussed the micro-hydropower system for sustainable microgrid using rural Africa as a case study [71], while [72] presented the overview of electrical power configurations for micro-hydro turbine systems.

The design of small hydropower production systems has been presented [73]. The voltage control of a virtual power plant is presented using small hydro power plants [74]. The authors discussed the possibility of achieving voltage control using the small run-off-river hydro power plants and introduced an energy management mechanism that connects the different components. A comparison of distributed model predictive control (MPC) strategies has been proposed for a hydro-power system [75]. A study has also discussed optimal scheduling for a distributed hybrid power system with pumped hydro storage [76].

2.2.5 Fuel Cells

Fuel cells are a type of DER that can continuously convert chemical energy to electricity as long as their steady supply of fuel and oxidant [35, 77]; however, the heat energy generated and the water formed in the energy conversion process is usually regarded as the by-products [78]. Several research studies have shown that fuel cells find application in distributed generation and combined heat and power applications [79, 80, 81].

The technologies are suitable for on-grid and off-grid applications. One of the challenges of the fuel cells is that the technologies have a limited load-following capability, which is why a hybrid configuration of fuel cells and microturbines, batteries, or ultracapacitors are usually proposed to solve the issue of limited load-following capacity [82, 83]. Another important consideration is that power electronic converters, effective control mechanisms, and grid synchronization strategies are required in their operation and integration with the existing distribution grid [35, 84 - 86]. These aspects are currently being considered by the research community to advance research in the area of grid integration of fuel cells.

2.2.6 Battery Storage

Battery systems are a type of energy storage technology that is employed in balancing the variability of renewable energy resources [38]. Besides, they are employed for some critical ancillary services in the grid integration applications such as voltage and frequency regulation, power quality, bridging power and energy management support. The voltage regulation support presented by the battery systems is considered a viable approach for mitigating the voltage rise/deviation issue when DG units are deployed in the distribution networks.

2.3 Voltage Rise Impact Analysis

The integration of DG with the existing power grid challenges the technical architecture of the grid system, which reflects in voltage, frequency and power quality distortions [87-90]. The analysis of the voltage rise effect in the distribution network is shown through a simple electrical circuit in Figures 1(a) and (b) where a DG is connected to the distribution system (assumed at 11 kV). The DG is a hybrid configuration of solar photovoltaic and wind power generation systems connected at the point of common coupling (PCC) through power electronic devices.

Where,

P_g and Q_g are the active and reactive power injected by the DG,
$R\ and\ X$ are the resistance and reactance of the feeder,
P_C and Q_C are the load active and reactive power,
$I_R\ is$ the current through the feeder,
$S_R\ is$ the apparent power on the feeder.

The voltage at the connection point V_g is:

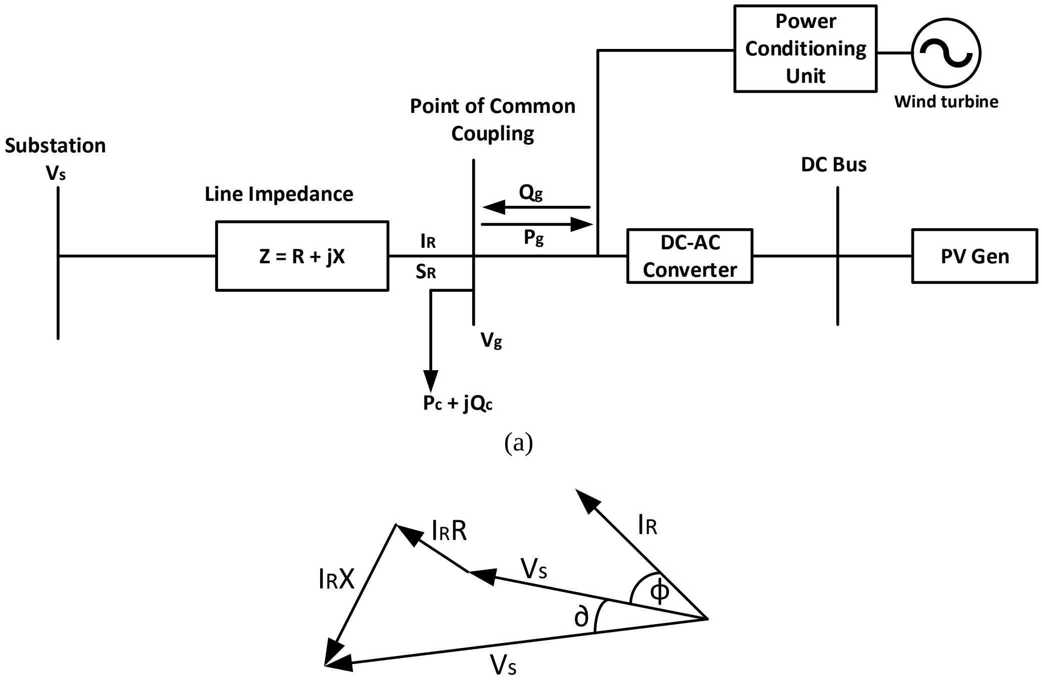
$$V_g = V_S + I_R Z \tag{1}$$

$$I_R = S_R^* / V_g^* \tag{2}$$

$$S_R = P_R + JQ_R = P_g - JQ_g - P_C - JQ_C \tag{3}$$

$$S_R^* = P_R - JQ_R \tag{4}$$

Therefore,



(a)

(b)

Figure 1. Voltage Rise from an Embedded Generator

$$V_g = V_S + (R + JX)(P_R - JQ_R)/V_g^* \tag{5}$$

$$= V_S + \frac{P_R R + X Q_R}{V_g^*} + \frac{P_R X + Q_R R}{V_g^*} \tag{6}$$

From the phasor diagram in figure 1,

$$V_g \sin\delta = (P_R X + Q_R R)/V_S \tag{7}$$

Since the voltage angle δ is very small, $(P_R X + Q_R R)/V_S$ is also very small and the magnitude of voltage rise ΔV $(i.e\ V_g - V_S)$ is approximately equal to:

$$\Delta V = (P_R R + XQ_R)/ V_g^* \tag{8}$$

$$= \{(P_g - P_c)R - X\,(Q_g + Q_c)\}/V_g^* \tag{9}$$

It can be seen from equation 9 that the voltage fluctuation issue will be more evident in the low voltage distribution network with high resistance feeder characteristics. Similarly, voltage variation depends strongly on the amount of active power injected by the DG into the network, which is why overvoltage is likely to occur during the period when generation exceeds the demand except some control and energy management mechanisms are put in place for voltage regulation.

Special technical arrangements are required to mitigate the impact of the voltage increase introduced by the DGs in the LV distribution network. Such solutions seek to balance the variabilities in voltage for quality energy supply in a grid with high penetration of renewable energy-based resources, without limiting or discouraging the proliferation of renewable electricity supply to the power grid.

3. METHODS TO CURTAIL VOLTAGE RISE

The approach to mitigate the overvoltage problem caused by the massive penetration of DG in the distribution network is classified into network reinforcement methodology and active distribution network management.

3.1 Network Reinforcement

Network reinforcement (NR) as an approach involves redesigning the existing distribution network to address and/or forestall the issue of voltage deviation and the associated exceeding of thermal limits of the lines when higher penetration of distributed generation systems is integrated with the power network. NR strategy in planning is associated with the cost of reinforcement of the DN; this is essentially the total cost of installation and operation of new feeders and transformers in response to the high penetration of DG units in the grid [91]. This technique is not practicable as the mitigation scheme will be less attractive due to significant techno-economic requirements involved. However, minor modifications may be necessary on the network or there may be a need to combine reinforcement with other voltage control methods to accommodate a higher amount of DG systems without violating the voltage limit.

Three methods are presented on the network reinforcement strategy, and these include the use of autotransformers on the feeder, installation of common DC link in domestic LV systems, and reconductoring. The adjustment of the substation and distribution transformer tap settings is being considered from the point of view of voltage and VAR control scheme.

3.1.1 Installation of Autotransformer on the Feeder

Traditionally, autotransformers (ATs) are mostly employed to boost voltages on the lines but they can also be modified to serve the purpose of voltage reduction. In this case, they have a voltage ratio of 1:1 and an on-load tap changer (OLTC) for the regulation of voltages [1]. When an AT is installed on a long distribution line, the line is automatically sectioned into two with the voltage and VAR control devices such as OLTC transformer, step voltage regulator (SVR), and line drop compensation (LDR), regulating one section while the autotransformer coordinating the other section. In other words, the installation of autotransformers - otherwise called voltage regulators, along the line is to introduce a form of re-setting of the voltage along the distribution system line when a high proportion of distributed generators is integrated with the existing network [5]. The disadvantages of incorporating AT with the distribution system are that they might affect the overall network security, reliability, and increase losses [5].

3.1.2 Installation of Common DC Link in Domestic LV System

The network upgrading, such as increasing conductor size to reduce the line impedance and the curtailment of DG output power when it poses a threat to power quality, are part of possible means to mitigate the impact of DG systems in DNs [92]. The former requires a huge capital investment while the former limits the proliferation of DG technologies. However, a common DC link technique in the LV network may be employed to increase the penetration of DG systems by allowing end-users (i.e. prosumers) to feed their surplus power to the existing grid [92]. In this case, the surplus electricity may be transferred to other phases and feeders via the DC link to ensure a balance between the power produced and the load [92]. Besides, the surplus electricity may be stored by the storage units for managing or shaving the peak load, and then be supplied to the end-users through the direct current or alternating current line. The DC link in domestic low voltage system does not only ensure higher penetration of DG units but also does not cause voltage quality, stability, and reverse power flow issues. One shortcoming of this strategy is the associated high capital cost.

3.1.3 Upgrading of Conductor

This approach is regarded as reconductoring [6], and it intends to reduce the resistance by increasing the conductor size [5]. The reduction of resistance is translated to the reduction of distribution feeder impedance, which is expected to allow maximum power generation output at all times. The result of this development is that the hosting capacity of the distribution system will be increased. In effect, reconductoring may be achieved by replacing the existing feeder with ones having a higher size or by bringing the point of connection of DG closer to the main substation using an extra line. It is obvious that the two options are expensive especially when the tasks involve the underground systems or they are to be carried out in major cities [5,8].

3.2 Active Network Management

Electric grid systems are in the dispensation of paradigm shift from stable passive DNs characterized by one-way power flow to active DNs with bidirectional power flow characteristics [44] Several factors are in support of the emergence of active DNs; these include end users' expectations of quality and reliable electric supply, decision-makers' interest and plan to integrate renewable DG technologies with storage systems, environmental sustainability plan of 50% emissions reduction in the next 3 decades, and the motivation of DNOs in the direction of effective asset utilization and management by deferring the construction of new T and D assets, etc. [44].

Several research studies exist in the literature that employs deterministic strategies to the issue of integration of DG technologies [93-96]. However, instead of using such approaches that limit the DG capacity that can be installed, active management of DN will allow more capacity of DG in the DN [97]. Therefore, the options available in this regard include the adjustment of tap settings of transformer and reactive power compensation – also considered as voltage and VAR control scheme, active power curtailment of DG, use of controllable loads, and energy storage devices.

3.2.1 Adjustment of Tap Settings and Reactive Power Compensation Schemes

This part includes the adjustment of the substation and distribution transformer tap settings and the reactive power compensation devices and control – also regarded as the voltage and VAR control devices.

The UK Electricity Supply Regulations, for instance, as reported about two decades ago, stipulated that the steady-state voltage rise of electrical power systems operating between 1 kV and 132 kV should be maintained at the value of +6 $\%$ of the nominal voltage, unless it is otherwise stipulated [5]. However, for systems above 0.05 kV and below 1 kV, voltage variations between +10 $\%$ and -6 $\%$ of the system voltage are allowed. At the initial stage, the Electricity Safety, Quality and Continuity Regulations did not propose immediate adjustments to the allowable voltage deviations but later proposed that the permitted voltage variations for systems operating between 0.05 kV and l kV were going to be adjusted to $\pm$ 10 % [5] from 2003 onwards.

The traditional practice by the distribution network operators at the planning stage is to keep the 11 kV substation slightly above the nominal voltage (e.g. 1.03 $p.u.$). This is being put in place to keep the voltage on other buses at the customer end within the permissible limit so that then voltage deviations appearing at the LV customer side remain within the allowable +10% and -6% window. Therefore, to forestall the issue of voltage rise in the case of a significant amount of distributed generation units on the distribution network, DNO usually considers the option of lowering the tap setting at the substation [5]. This may be achieved by careful consideration of the possibility of some customers on the network experiencing voltage depression especially during the worst-case scenario of no generation and peak load. Besides the contributions discussed in [5], the study presented in [89] has also shown that a careful adjustment of the LV transformer tap setting is an effective technique for curtailing voltage rise issue in the distribution network with high penetration of distributed generators.

Voltage control has, for a long time, been achieved in the distribution network through the activities of voltage and VAR control (VVC) devices. These devices include the on-load tap changer (OLTC) transformers at the substation, step voltage regulators (SVR), and switched capacitors (SC) on the feeders [3]. The SVR control operates by continuously measuring the load current and voltage and then adjust the transformer tap position following the discrepancy observed between the measured voltage and the reference set-point voltage. SC supplies reactive currents on the line thereby minimizing voltage drop [98].

Such voltage control scheme is designed with some assumptions, inter alia, a radial power flows from the substation to the load, circuit loading pattern on the line is predictable and voltage drops monotonically from the substation. The introduction of DG invalidates these assumptions and this scheme becomes inherently insufficient as it does not extend to the low voltage 400 V network level and this may lead to violation of voltage limits during high DG supply and low demand.

In Figure 2, The voltage V_3 is measured by the SVR and the tap position in the transformer primary winding adjusts in such a way as to keep V_3 within the pre-set limit. However, there is no accessibility to the value of

V_4 at the other side of the line and this may cause V_4 to exceed the limit during low load and peak generation even when V_3 is kept within range. The line drop compensation (LDC) feature, which is also part of the SVR control, evaluates the line voltage drop between V_3 and V_4 by an appropriate simulation circuit that is fed by a voltage at the secondary winding of the OLTC transformer and by a small proportion of the line current. From the simulation, a voltage drop that models that of the line is established and used as a control signal for the OLTC thereby maintaining the voltage V_4 within the statutory limit. LDC could be adapted as line rise compensation (LRC) to perform voltage correction during voltage rise [1].

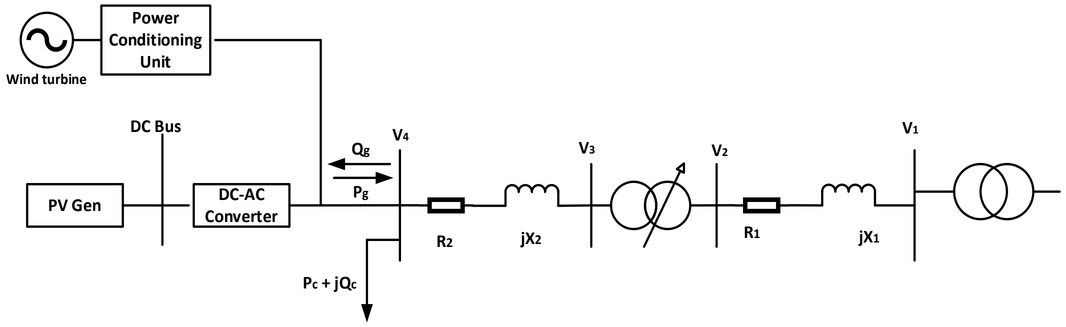


Figure 2. OLTC transformer with DG

Capacitor banks have been traditionally used to boost the voltage on long feeders. In order to adapt them for voltage reduction, a system of reactors may then be needed or FACTS devices such as static Var compensators (SVC) and Static Synchronous Compensators (STATCOM) as discussed by [107-109]. However, getting the optimal set points for FACTS devices is not straight-forward because the design of the distribution system can be modified at a later time. Similarly, reactors are linked with higher power losses than capacitors and can also cause disturbance to the voltage regulation relays [110]. Generally, this scheme can be a good option only when the extra VAR requirements are limited as the equipment capital cost can be considerably high.

Several studies have been presented to advance the reactive power compensation aspect of the power system. For instance, a paper has been published on a centralized reactive power compensation system for low-voltage DNs [111]. A reactive power compensation and optimization approach has been proposed for grid-interactive cascaded solar photovoltaic power systems [112]. The authors presented the possibility of realizing high-power photovoltaic systems by employing a cascaded multilevel converter structure. However, voltage and system operation problems arise as a result of the power mismatch from cascaded individual solar photovoltaic converter units. The study introduced coordinated real and active power-sharing to mitigate the identified problem.

Generators can either operate in power factor control (PFC) mode or automatic voltage control (AVC) mode. The PFC mode implies that whenever the active power output changes, the excitation current of the generator will be adjusted accordingly such that the VAR output keeps the power factor constant. On the other hand, a generator in AVC mode will vary its excitation such that its output VAR continues to maintain the voltage at a reference set point. As such, a generator operating in PFC mode will increase its reactive power output as the real power output increases. This rise may become intolerable in weak distribution networks with a high *R/X* ratio and the DG will be required to go offline or reduce its power [113].

Formerly, DNO, through [114] only permits the operation of DGs in zero reactive power or APF mode, the reasons being that the size of a single unit DG is relatively small to control system voltage and the AVC settings of DG may conflict with those of network equipment such as OLTC transformer operation thereby increasing the risk of islanding [115]. However, the revised [116] has allowed DG to participate in distribution system voltage regulation which means that synchronous generators and self-commutating inverters, can reduce or import, as the case may be, their VAR output to provide system voltage support.

For the reactive power Q to offset the voltage rise caused by active power $P,$ then we must have $Q = -\Delta RP/X$ where $R\ and\ X$ are the feeder resistance and reactance [66]. It is obvious that as the value R/X increases, so is the Q required to counteract voltage rise. Therefore, such regulation by DG may not be adequate as this might result in a low DG power factor during low or high network voltage conditions thereby reducing the ability of DG to produce active power. When DG regulation is near an operating limit in AVC mode, it will automatically switch to PFC mode [98]

The work presented in [2] has shown that a hybrid voltage control method that combines the advantages of AVC and PFC can improve the voltage profile and keep DG in operation during both light and heavy load periods thereby increasing net energy dispatch. The method is referred to as automatic voltage/power factor control (AVPFC). Its operation is shown in the vector diagram of Figure 3 [117].

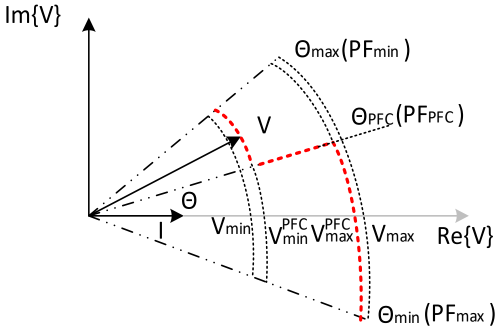


Figure 3. Voltage vector diagram showing AVPFC operation

The thick dash line represents the path of the DG operating point while V_{min} and V_{max} and the statutory limits of voltages. When voltage approaches these limits, the PFC mode is relaxed and AVC mode takes over by absorbing or generating the required reactive power to ensure voltage limits are not violated. At V_{min}^{PFC}, the P/Q ratio is decreased while at V_{max}^{PFC}, the P/Q ratio is increased. As the power factor is also being affected while changing the P and Q ratio, it must be constrained between PF_{min} and PF_{max}.

The AVPFC is beneficial in that the scheme relies completely on the voltage information at its end and does not need to be aware of the distribution system as a whole. Hence the approach does not need communication equipment installation and the controller can be embedded within the generator control system [117]. This method has been successfully applied by [118] and [119] have also proposed varying DGs between leading and lagging power factors to mitigate voltage rise.

Studies by [120-122] have investigated the capability of PV inverters to generate reactive power to provide voltage support to the system and the method has proven to be effective and economical as it neither requires extra investment nor does it cause wastage of solar energy. Similarly, as the capacities of PV inverters are not often fully utilized, the residual capacity can be employed to deliver reactive power to the network. However, reactive power import by the PV inverters may put more stress on them and reduce their lifetime [123].

3.2.2 Active Power Curtailment

With the highly resistive line characteristics and large R/X ratios in the LV network, the voltage profile is highly dependent on the active power than the reactive power. Therefore, active power curtailment (APC) is more effective at reducing overvoltage than reactive power control. The control systems available in the modern days will permit a DG to control its output in accordance with the network voltage. This may be a beneficial approach for wind generators which rarely produce power to its rated capacity due to the nature of wind and load factors [97].

Similarly, the power conditioning subsystem (PCS) of the PV system is equipped with a network over-voltage protection function and regulates the output power of the PV system. To mitigate the voltage-rise issue, it is now obligatory for network-connected inverters to regulate their output power according to the network voltage [99, 100].

The research study in [111] has presented a real-power capping approach to control voltage profiles of LVDN by setting the power limit for PV inverters in real-time. However, APC leads to a reduction in the revenue of the DG owners as the power output is reduced. The grand challenge with this mitigation approach is that it jeopardizes the opportunity for widespread application and proliferation of DG technologies.

3.2.3 Use of Load Control

The use of controllable loads is one of the mitigation approaches for the integration of DG technologies in DNs. Several existing studies have attempted to discuss the theory and application of load control as a means to manage the issue of voltage rise in LV distribution DNs. The study in [8], for example, has proposed the use of controllable loads such as those capable of storing energy for the purpose of voltage regulation. During the period of high generation and minimum load, the extra load is automatically switched on by the control system to prevent the voltage limit from being exceeded.

The paper in [102] has also demonstrated that load control can be economically attractive in allowing more DG to be connected. This is because the stored thermal energy can be used at a later time and the control action will only operate in a limited period. It is worth mentioning, however, that this scheme requires a major capital investment but it can compare well with other methods such as grid reinforcement.

3.2.4 Energy Storage System (ESS)

ESS such as a battery energy storage system (BESS) is an effective method to store excess energy during peak generation period and minimum load. BESS has the capability of absorbing and releasing both active power and reactive power with a fast response time [103]. The idea of storing excess renewable energy, for instance, and then selling it back to the grid during peak periods is referred to as energy arbitrage [39].

High capital cost and low life-cycle are major factors that impede the widespread usage of this scheme. In addition, the life span of the BESS is limited by its charge-discharge characteristics. However, several studies exist in the literature that has shown the viability of integrating BESS with the existing grid system. For instance, [104] has presented an approach for selecting the most economical energy storage configuration that combines the optimum capacity of PV generation with the right capacity of ESS.

A coordinated control of multiple energy storage systems has been proposed by [105] to regulate the network voltage based on the battery aging model. Also, the application of BESS has been considered for improving transient responses in a DN [106]. The motivation for this study is the fact that increased penetration of renewable electricity production systems could result in voltage and frequency stability challenges in DNs due to the variable characteristics of the resources. The integration of BESSs with the grid has been considered by the authors as a possible means to enhance the dynamic performance by balancing the variabilities in voltage and frequency. This was achieved with the capability of BESS for injecting/absorbing active and reactive power to maintain the balance in the network.

4. COOPERATIVE VOLTAGE CONTROL STRATEGIES

To adequately mitigate the voltage rise issue in a distribution network with a significant amount of DG, it is necessary to employ two or more voltage regulation schemes in combination. For instance, the voltage control scheme based only on the management of DG reactive power is limited in its effectiveness due to the high resistance characteristic of the distribution network. Therefore, an approach that integrates reactive power control with active power curtailment will be more reliable. Such cooperative strategies have been grouped into local voltage control, distributed voltage control, and centralized voltage control.

4.1 Local Voltage Control

In this scheme, the control commands are decided based on local measurements and require no complex communication infrastructure, and therefore, the scheme is less expensive. Local voltage controls can provide a fast action as they only have to monitor local voltage and/or DG power production and thus can be deployed as an online application. However, due to a lack of coordination units, the available capacity in the entire network may not be optimally utilized [120].

Local voltage control methodology has been employed successfully by [124, 126] to regulate voltage by combining the APC technique with PV inverter reactive power control. voltage fluctuation in the distribution network with PV generation was minimized by optimizing active and reactive power generation of the inverter. An algorithm that employs APC in conjunction with PV power forecast and a droop-based reactive power has been proposed and studied. [126] have combined voltage-dependent battery charging, automatic reactive power provision, and PV power curtailment in a local control scheme to regulate voltage in the distribution network. The proposed method by [127] uses a local droop-based control of BES positioned at each house in combination with the reactive potential of PV inverter to adequately keep voltage range within the permissible limit in rural network with high resistance feeder.

4.2 Distributed Voltage Control

The quest for real-time control resulted in a scheme capable of sharing information among multiple controllers. The sharing of tasks among neighboring units therefore employs limited communication links [125]. A distributed control scheme based on a multi-agent system [129-132] has been proposed and studied by [133]. The study concluded that using a distributed control approach rather than a centralized architecture could improve: (a) scalability and openness, (b) resilience and reliability, and (c) communication efficiency which are lacking in a centralized control scheme.

The study in [115] employed distributed reactive power control in a cooperative approach with OLTC transformer coordination. The study revealed an improved voltage regulation but at the cost of increased stress on the tap changer mechanism. A distributed algorithm has been proposed by [134] to curtail overvoltage by controlling the real and reactive power injection.

4.3 Centralized Voltage Control

The DG optimal performance is determined by solving an optimal power flow (OPF) problem for coordinating voltage profiles among multiple pieces of equipment. It requires a global communication between the primary substation and the widespread sensors on the distribution network and a central controller initiates an action to coordinate other intelligent units in the network [135]. This scheme is expensive to set up owing to the cost of the control center and communication networks. Also, the installation of a new DG on the network would require modification in the programming of the central controller. This could be burdensome and complicated [133].

A centralized control scheme that derives optimal real and reactive power set-points for inverters has been studied by [136-138] has proposed a centralized control method for coordinating energy storage systems and OLTC transformers to improve voltage profile in the distribution network. Centralized information has been used to obtain the optimal reference value for OLTC transformer operation and PV reactive power by [110]. Furthermore, [125] has used a centralized control method to coordinate various controllers according to voltage level and active power curtailment.

4.4 Techno-Economic Comparison of the Mitigation Approaches

Several energy conversions have taken place before electricity is produced from the DG systems. This usually involves the processing of primary fuel to extract the heat or calorific content that is now converted to electrical energy through the generator. Besides, the output of the DGs is not directly fed to the grid without an interfacing device such as the power electronic converters – DC – AC and/or the power conditioning units. These processes have cost implications, which is why it is important to consider the resources and efforts expended in constructing DGs in technical and economic terms, including the type of DG when deciding on the kinds of mitigating approaches in a situation where there is voltage rise resulting from the grid-connected DGs.

The mitigation approaches are determined by some factors such as the technology involved, ease of deployment, cost implication, and their pros and cons. These are used as criteria for comparing the different mitigation strategies for the problem of voltage increase in the LV network.

Redesigning existing DNs to forestall voltage rise due to higher penetration of DGs, for instance, is not always viable and may make the scheme to be less attractive. This is because of the complexities and the cost involved.

Technically, the installation of autotransformers (ATs) on the system feeder can provide a voltage boost on the lines and may also serve the purpose of voltage reduction. However, ATs may pose a threat to the security and reliability of the network, and can also lead to an increase in losses. It also has cost implications. The adjustment of substation and distribution transformer tap settings, as a technique to curtail voltage rise, can help to keep the voltages at the buses at or near the customer end within acceptable limit by making the primary distribution substation voltage a bit higher than the specified voltage. Also, a lower adjustment of the tap setting at the distribution substation to forestall voltage increase is also a technique employed for the high penetration of DG technologies on the existing network. On the techno-economic side, this approach is less complicated and cost-effective compared to the use of ATs on the system.

The installation of a common DC link in a domestic low-voltage system can accommodate a significant amount of DG systems, whilst also suppressing voltage instability issues. However, this approach has a huge capital investment implication compared to the adjustment of substation and distribution transformer tap settings. The upgrade of the conductor to reduce the feeder impedance is another option that is expected to increase the hosting capacity of the distribution network, hence permitting the maximum electrical power generation all the time. The hosting capacity in this case is the amount of DG technologies that could be accommodated by the network without the requirements for system or infrastructure upgrades or without any adverse effects on the voltage or power quality of the power system. Traditionally, this technique may be achieved by conductor upgrades or bringing the PCC nearer to the main distribution substation by employing an extra line. However, this is also a very expensive option. Conductor upgrades are a tedious task that may also involve supply interruption.

The use of voltage and reactive power control devices, on the other hand, has traditionally been a method of achieving voltage control in distribution systems. As mentioned earlier in the previous section, these options include the OLTC transformers at the distribution substation, step voltage regulators (SVR), and the switched capacitors (SC) on the system feeders. The SVR control measures the load current and voltage and then adjust the transformer tap setting in accordance with the mismatch between the measured voltage and the reference set-point voltage, while the SC in its mode of operation supplies reactive currents on the line thereby minimizing voltage drop, as mentioned earlier. One of the technical shortcomings of this scheme is that it does not cover the low-voltage (400 *V*) level, which may cause a voltage limit violation as a result of the high-power generation from the integrated DG systems and low load demand. The shortcoming of the active power curtailment (APC) approach is the reduction in the revenue generation of the DG planners as a result of the limit placed on the power output of the DG technologies. The APC is one technique that is capable of placing a limit on the economic prospects of DG systems, which can affect the proliferation of the technology.

The use of controllable loads is also an option for addressing the voltage increase issue by providing the storage of energy for voltage regulation. As mentioned earlier, it can lead to the integration of a high percentage of DG systems. However, it is limited by huge capital requirements just like the energy storage, reactive power compensation – SVC and STATCOM schemes. The idea of reconductoring in distribution networks as a means to mitigate the voltage deviations due to high penetration of DG systems also has a huge cost implication.

5. RECENT TRENDS IN DN WITH DG AND FUTURE DIRECTIONS

5.1. Recent Research on Grid-Integrated Systems

The DN is very vast and highly dynamic due to a lot of techno-economic factors. The integration of DG to provide support to the DN may cause severe damage at the consumers' end due to the voltage rise problem, especially when a high proportion of the DG units are integrated presenting a cumulative effect to the existing network. Consequently, several methods have been developed and deployed to address this technical problem. As research studies progress in the aspect of the integration of distributed generation, it is of interest in this paper to present the trends of contributions by power and energy scholars within the research community. Some of the techniques for mitigating the voltage rise problem in DG penetration are presented in detail to keep the readers abreast of the recent trends and state-of-the-art approaches in relation to DG integration and applications.

A multi-stage sizing approach has been proposed for the development of utility-scale BESS with emphasis on the dynamic growth of distributed solar photovoltaic connection [139]. The authors introduced an integrated model that has the capability to accommodate embedded solar photovoltaic generation on a short-term operational scale while ensuring benefits on a long-term planning basis. The strategy includes cluster wise reduction to obtain the most relevant scenario-based integration of photivoltaic array and battery systems. Such a strategy presents the possibility of minimizing the complexity associated with computing brought about by scenario redundancy. The model is tested using the IEEE 69-bus distribution system, which provides insights to verifying its feasibility from the point of view of the multi-stage sizing approach for the utility-scale BESS. The results demonstrate the capability of the proposed approach to provide an optimal multi-stage basis for utility-scale battery sizing for various growth trend of distributed solar PVs. BESS can contribute to the enhancement of reliability, optimization of the voltage level, shifting of the demand profile, economic benefit, and the other ancillary supports [140-142].

An online reconfiguration of active distribution networks has been presented for achieving maximum integration of distributed generation [143]. The idea put forward by the authors is the fact that the combination of the control for the active/reactive capacity of DG systems with the remote-controlled switches are used for minimizing DG power curtailment, reducing line congestion, and mitigating the voltage increase problem when DG technologies are integrated with the existing network. The authors adopted the “convex relaxations” of the load flow relations and the “mixed integer linear disjunctive” formulations with the optimization strategy to realize fast and optimal results through the standard branch and bound solvers. It was reported that the associated burden with the optimization method is reduced by utilizing the evaluation of switching actions achieved through several generation versus load scenarios. The results of the study and analysis reveal that the proposed distribution network reconfiguration has the capability to offer active network management and control to eliminate DG curtailment, thus, translating to a maximum integration of DG capacity to the network.

Such a model can help promote the widespread application of distributed generators notwithstanding the voltage rise at the PCC and the associated issue of two-way power flow direction.

The application of transactive control (TC) has been proposed as a framework for operating electrical power networks with high penetration of DERs [144]. The study began by introducing the background knowledge and features of TC. It presented a comprehensive overview of recent developments in TC application and relevant framework suitable for operating electrical power networks with a high percentage of dispersed generators. It also illustrated the implementing techniques for realizing TC through information exchange (IE) between the participating actors and components. The implementing approach - a means by which equilibrium is sought among the actors to complete the intended transactions. This could either be in form of a one-time IE-based technique or an iterative IE-based technique. An example of the former is the merit-order-based market-clearing scheme, while the latter is associated with dual composition computing algorithms. A conceptual TC framework presented in [145] aims to optimally control and manage the interaction of “self-interested” independent stakeholders, participators, or decision-makers that emerge in the electrical power distribution system.

A study has been presented on voltage control in LV distribution networks with high penetration solar photovoltaic power system [146]. It has already been established that a high percentage of dispersed generators can lead to voltage increase problems in the DN. This necessitates the voltage control mechanisms to keep the voltage levels within the acceptable limits for generation versus load conditions. The study proposed a global voltage control (GVC) scheme in LV distribution systems for maintaining the voltage within the set limits. A minimum reduction of the active power injection capacity of the distributed PV generators is achieved by a varying power factor based on the non-linear programming (NLP) model. The results show that the control scheme with NLP has less power curtailment compared to the one with linear programming (LP). This implies that there is a greater benefit for less power curtailment compared to a situation whereby the curtailment is high.

The management of voltage regulators in unbalanced distribution networks has been proposed using the voltage/tap sensitivity analysis [147]. The authors proposed an optimal voltage management scheme for unbalanced DNs. Such a strategy is based on the voltage/tap sensitivity analysis and different voltage regulators are considered with dissimilar connection configurations. The numerical analyses were tested on different IEEE 13-bus and 37-bus systems. The results demonstrate that the proposed scheme can optimally manage the configurations of the voltage regulators without outrageous oscillations of the tap. The results further indicate the possibility of effective mitigation of voltage problems associated with high penetration of dispersed generators.

The optimal planning of PV inverter is proposed in the presence of capacitor bank in medium-voltage DNs [148]. The authors first maintained that the voltage regulation issue is dependent on the capacity and the location of the distributed PV, loads, and the topology of the distribution feeder. An approach was proposed to address the voltage increase problem by optimally increasing PV inverter capacity over the PV array capacity with the integration of a reactive power compensator based on capacitors. The optimization model considered the overall system constraints and the proposed scheme is tested with IEEE 119-bus DN. The performance of the proposed model and strategy is ascertained by assessing the optimal PV inverter capacity for minimizing the voltage rise and the voltage deviation from the specified voltage window. An optimal control strategy has also been presented for a 3-phase islanded microgrid system [149].

A study has considered the determination of optimal location and sizing of distributed solar photovoltaic generation units in radial DNs [16]. The authors introduced biogeography-based optimization (BBO) approach for realizing the optimal sizing and location of distributed PV generation units to reduce power losses, maintaining the voltage profile and voltage harmonic distortion or deviation within the specified limits. The algorithm is based on the concept of biogeography – the distribution of “biological species in time and space. The strategy can spread the space for searching and then keep the desired group at each generation, thus, achieving a significant performance enhancement. The performance of the algorithm introduced is validated by testing it with the IEEE 33-bus and IEEE 69-bus radial DN systems. It was found that the proposed algorithm used in the BBO approach offers a better solution in terms of quality and precision with rapid convergence when compared with the genetic algorithm, the particle swarm optimization algorithm, and the artificial bee colony algorithm.

The voltage regulation-oriented co-planning has been proposed for distributed generation and battery storage in active DNs [150]. The authors first described an active DNs as electric power networks that integrate large-scale DG and storage systems, and then proposed a novel 2-layer planning approach for realizing the optimal location of inverter-interfaced distributed generators and the battery storage system. The overarching goal of the proposed strategy is to improve the voltage regulation tasks within the active DN. The 2-layer approach includes outer-layer and inner-layer aspects. The role of the outer-layer model is to ascertain the planning decision of the distributed generators including the inverter sizing, location, and capacities of battery banks, while the inner-layer model seeks to determine the operation decision with respect to the optimal schedule of the battery systems' charging/discharging characteristics and the VAR from inverters for voltage regulation purposes with respect to conservation voltage reduction (CVR). CVR in this case is described as an energy-saving strategy introduced to reduce the voltage magnitude to the least allowable range to minimize the electrical load demand [151]**.** The CVR is realized by hybridizing the DG and the battery units for the energy-saving task. The validity and effectiveness of the proposed model are tested using the modified IEEE 33-bus radial DN.

The stochastic hosting capacity in LV DNs has been discussed [152]. The authors described the hosting capacity as a level of penetration that may be permitted for a particular technology in the DN without creating power quality problems. The impact of distributed photovoltaic power generation on the voltage rise. In most cases, the sizes and placements of the DG are usually not known initially and some existing studies examined the problem by considering a huge number of scenarios with only little additional information. An effort was made in this study to address the mentioned shortcoming by examining only cases with active voltage constraints to reduce the required number of scenarios through an order of magnitude. The idea presented by the authors is the linear power flow model to achieve the task, which demonstrates excellent performance. The results demonstrated that the proposed model can significantly reduce the system's total cost of operation with solar generation, battery peak-load shifting, and the CVR mechanism. It can maintain the system's voltage profiles in a specified range by coordinating the inverter-interfaced DG, battery bank, and the existing voltage regulation systems.

The superconducting magnetic energy storage (SMES) has been proposed for stabilizing grid-integrated wind power generation systems [153]. The authors attributed some of the voltage quality and frequency stability issues experienced in modern electric power network to the integration of different renewable energy and adaptive technologies. SMES has been considered because of its dynamic characteristic, efficient rapid exchange of power with the existing grid in situations where there are small and large perturbations to mitigate the instabilities. Such technology helps to control the output power of distributed wind power generation, thus, improving the stability of the electrical power system. It was established in the study that the application of SMES depends on the proper location in the DN, actual electrical and energy capacities, including appropriate control devices. The idea presented in this work is about the utilization and controllability of SMES to mitigate the issue of stability when distributed wind generation is integrated with the power grid. The authors used a multi-objective, multi-area optimization approach to achieve the benefits of SMES technology.

A simplified analytical approach has been proposed for the optimal planning of DG in electrical DNs [154]. The authors recognized power losses as one of the operation chacacteristics that vary when distributed generators are integrated with the existing network. Besides, it was established that the number, location, size, and power factor are parameters that affect the the quantity of power losses. These parameters are also believed to affect the voltage profile. A novel analytical approach was proposed for the optimal allocation of DG units to reduce power losses in DNs. The research study considered using and assessing different DG parameters to achieve a significant loss reduction in the DNs. The proposed algorithm was implemented in a MATLAB environment with its performance tested on 12-bus, 33-bus, and 69-bus IEEE DN test systems. The results demonstrate that the proposed technique can provide a precise solution through the simple algorithm devoid of exhaustive power flow computation tasks.

The sequence component-based improved passive islanding detection method has been proposed for DNs with distributed generation technologies [155]. The authors identified a shortcoming of passive islanding detection strategy in terms of their incapability of determining or detecting island the results in a slight power imbalance. The study proposed an improved passive islanding detection approach base on two newly developed indices emanating from the current signal "sequence components" and the traditional voltage and frequency parameters. The effectiveness of the proposed approach is tested for some islanding and non-islanding scenarios using the IEEE Std 399-1997 and the IEC model DN system connected with inverter-interfaced and synchronous DG units through the PSCAD/EMTDC. The authors presented results that reflect an effective islanding scheme.

A multi-objective framework has been designed for enhancing the voltage stability in DNs [156]. The focus of this study was to investigate the performance of a radial DN with distributed generators using various kinds of DG units for different DN configurations. A Voltage Stability Index (VSI) was employed for determining the location of the DG units in the distribution grid. The authors proposed a multi-objective framework to assess the DG capacity to be integrated based on the reduction in power loss and the deviation in bus voltage.

The optimal sizing of the DG has been based on the Genetic Algorithm. The proposed approach was tested on standard DNs such as the IEEE-33 bus and IEEE-69 bus systems having different radial DN configurations. It was reported that the proposed framework realized good results in terms of reduction in power losses and voltage deviations in the DN.

A temporary fault ride-through technique has been presented for power distribution systems with DG units based on power conditioning systems (PCS) [157]. The authors identified the disconnection of DG units for every fault in DNs as an adverse development on the utility and steady power exchange and trading when integrating a large-scale distributed generator. This implies that during fault detection and circuit breaker reclosing at the occurrence of a temporary fault, the DG systems are required to be disengaged or isolated from PCC before the circuit breaker reclosure. In this case, the DG units are configured to wait for a minimum of 5 minutes after they are restored for reconnection in which there will be customer-minutes lost during such a period. This study focused on how to address this problem by proposing a control technique referred to as the temporary fault-ride through that is capable of maintaining continuous operation without disconnecting the DG. This control method is modeled and simulated in PSCAD/EMTDC environment for DNs with DGs based on PCS and the circuit breaker reclosing protection.

A reliability-based network reconfiguration model has been designed for DN with distributed generation and energy storage systems using mixed-integer programming [158]. The authors first mentioned that a widespread application of DG units and energy storage systems helps a DN to achieve a suitable and flexible fault reconfiguration capability. They proposed a novel DN reconfiguration model that includes the DG and energy storage units to enhance the reliability of operation and the benefit of DNs. The study also examined the effect of “sectionalizing switches” (SSs) and tie-switches on reliability. The proposed model is aimed at minimizing the customer interruption cost, the operation cost of switches, and the depreciation cost of DG units and storage systems. The proposed model is then translated into mixed-integer linear programming, which can offer an efficient and ease of achieving solutions. The model was validated and tested using the modified IEEE 33-bus and PG&E69-bus network systems. The authors reported that the integration of distributed generators and energy storage systems offers a reduction in outage time, suggesting that the kinds and placements of SSs have a significant impact on the resulting benefits provided by the DG units and the storage systems.

A protection coordination strategy of radial DNs with DG has been proposed considering auto-reclosing schemes by Resistive Superconducting Fault Current Limiters (RSFCL) [159]. The paper first established the fact that fuses and reclosers are normally used to protect the radial DNs against fault currents by fuses. Such protection is managed or coordinated in a manner that temporary faults are cleared by reclosers before the fuses melt to clear permanent fault conditions. However, recloser-fuse management may fail when distributed generation technologies are connected with the DNs because of the current flowing from the DG systems during the fault period and the alteration of the radial characteristics of the DN. The penetration level, location, and type of distributed generation technologies determine the technical impact of recloser-fuse management. The authors investigated the effectiveness of RSFCL to restore recloser-fuse management without examining the auto-reclosing strategy. The authors proposed solution approaches that are based on three dissimilar RSFCL configurations to keep the management of recloser-fuse when the auto-reclosing strategy is being taken into consideration. The analysis and simulation were done in MATLAB/Simulink environment and results indicate the capability of the proposed RSFCL model to maintain recloser-fuse coordination. All simulations are performed using the MATLAB/Simulink package.

A two-level centralized and local voltage control has been presented for mitigating the effects of highly intermittent renewable generation on DNs [160]. The authors proposed a method for voltage control and ensuring optimal power flow (OPF) operation of radial DN by managing and controlling the VAR contributed by DERs. The two-level control mechanism consists of an upper-level centralized control device and a lower-level local control device. The study presented a stable local control strategy (LCS) and an indicator for voltage stability based on a discrete-time state-space model. Furthermore, LCS is integrated with a centralized OPF optimization scheme to reduce power losses in the DN while ensuring optimal values of bus voltages. The proposed control system is modeled and simulated in MATLAB/OpenDSS environment based on real-life input data, and it was tested on the IEEE 123-bus test system with historical data of load demand and distributed PV generation for 24 hours. It was reported that the proposed control technique improved the existing local control mechanisms with more rapid convergence, and also ensured the minimization of voltage variations in a situation where a large-scale intermittent renewable generation is integrated. The voltage imbalance and transformer tap changer operations were also reduced.

A holomorphic embedding load flow (HELF) modeling of DSTATCOM has been presented for active DNs [161]. The authors established that conventional load flow convergence failure is experienced when large-scale distributed generators are integrated with the existing DNs. This has been attributed to heavy power transmission. The HELF modeling has been considered to be more robust compared to the traditional Newton-Raphson technique in the case of heavy power transmission and is insensitive to the initial points of the analysis. Traditionally, HELF modelling is employed for balanced transmission grid systems. However, the idea presented in this study is the design and application of a 3-phase HELF model to integrate distributed generators, $\Delta -$connected loads, and ZIP loads for active DN. The performance and effectiveness of the proposed HELF modelling approach under heavy load conditions were tested with modified unbalanced IEEE 13, 34, 37, and 123 test bus feeders.

A coordinated real-time voltage control (CRTVC) method has been proposed for increasing the penetration of DG systems [162]. The authors also identified the voltage rise problem as one of the major concerns of integrating DG systems with the existing DNs. They recognized active power curtailment as a means of addressing the issue of voltage rise in several existing voltage control strategies, which has an adverse effect on the economic side of the DG investment and the application of DG systems. The study proposed the CRTVC technique with the intent of controlling DN’s voltage profile while presenting active power curtailment of the intended DG units. Such a technique was meant to reduce voltage deviations by ascertaining the regulator taps and VAR contributions of the capacitor banks and the distributed generators. The proposed algorithm was validated and tested on the IEEE 33-bus system. The results show the capability of the CRTVC technique to effectively control the voltage profile with rapid convergence of the analysis. The authors also posited that the elimination of the issue of voltage deviation associated with DN that integrates DG systems provides an economic means of growing the penetration of DG technologies.

A multi-energy-storage energy management (MESEM) technique has been proposed for DNs with DG systems [163]. The authors identified that the variability, volatility, and “anti-peaking” characteristics demonstrated by distributed renewable electricity generation technologies pose challenges for the smooth and economic operation of power DNs. They proposed a novel MESEM system for co-optimizing the electricity-based mobile energy storage and inverter air-conditioning-based thermal energy storage (TES) systems. To aid the energy management of the distribution network, the MESEM was designed to consider the delay factors, while the TES was meant to regulate the VAR reactive, and these are configured and developed into a “unified analytic” model that has the capability for charging and discharging. Also, the authors proposed a novel and effective optimization technique to obtain a more precise worst-case scenario. The authors converted the dispatching model to mixed-integer second-order cone programming and mixed-integer linear programming problems; and the linearized approaches and an iteration method were employed to solve the mentioned problems efficiently. The simulation results obtained from using a 41-bus DN in Ontario as a test case demonstrate that it is possible to reduce the electrical power loss and the cost of operation of the distribution network can be reduced by 8% and 1% by employing the proposed MESEM, while it is also possible to obtain a voltage deviation of 5%. The results indicate the capability of the proposed model for ensuring peak shaving, valley filling, and voltage management support.

A control approach has been presented for mitigating voltage unbalance in DNs with rooftop PV systems based on distributed battery storage systems [164]. The authors first maintained that unbalanced loads are a factor that generates voltage unbalance beyond the acceptable limit in 3-phase 4-wire LV DNs integrated with rooftop solar photovoltaic systems. They proposed a control strategy that mitigates the voltage unbalance by introducing restrictions based on distributed battery storage systems that are added to interface the grid and the rooftop solar PV systems. The strategy is essentially a dynamic control model that is based on two PI-control devices for ascertaining the batteries’ compensating currents requirements and ensuring equality “resultant stress current” on each of the system buses. The optimal coefficients of self- and mutual-sharing of each battery system were evaluated by employing the PSO and Bat optimization approaches. The model was implemented in a MATLAB environment and the results reveal mitigation of voltage unbalance on the DN.

A study has considered solar photovoltaic power generation systems in LV networks and overvoltage correction using a reactive power control [165]**.** The authors examined the voltage increase beyond the specified limits and then suggested some approaches for addressing the challenge of an overvoltage by controlling the reactive power of the solar PV inverters. A topology was introduced based on a three-phase LV radial network with dispersed solar PV systems and residential loads. The simulation is based on real users’ data and solar radiation measurements. The paper introduced three different overvoltage correction approaches with reactive power control. In the first two strategies, the VAR that is consumed at the system nodes is provided by the power network, while in the third strategy, the VAR that is consumed at the last nodes is provided by the DC-AC converters at the first nodes, thus, ensuring that the excessive VAR is not fed by the grid.

5.2 Future Research Projections

The paper presents the review of technologies, impact and mitigation approaches with respect to the voltage rise problem that is created when distributed generators are integrated with the existing DNs. It discusses recent research studies and progress made on different techniques for addressing issues associated with the grid-integration of distributed generation. However, it is necessary to present important directions for future research, to provide insights into advancing knowledge in the aspect of the interaction of DERs with the existing grid. Addressing the voltage rise problem will also translate to the solution of other technical issues such as exceeding the thermal limits, etc.

It is obvious that electrical networks will continue to be smarter. This suggests that future DNs will possess the technical capability to integrate and accommodate a higher proportion of distributed generation technologies more than what currently obtains around the world. As mentioned earlier, these technologies could be based on conventional and non-conventional resources, including the other DERs such as battery storage systems, fuel cells, and electric vehicles. Therefore, it is expected that future research will focus on a more integrated approach for planning, designing, modeling, implementing and managing active DNs with distributed generators. Such an approach will benefit from the complementary features of some of the existing techniques towards mitigating the impact of voltage deviation on the DN while ensuring the deployments of a high percentage of distributed generators. Since the determination of size and location of DG systems is one important scope of grid-integration studies, then it is expected that the integrated approach will include a multi-objective optimization task that seeks to obtain the optimal size, location and cost of DG while addressing the technical issue of voltage deviation and increasing DG deployments in the distribution network.

Recent developments have shown that it is possible to employ the superconducting energy storage technology (SEST) for addressing the issue of voltage instability caused by the influx of DG systems in DNs. SEST possesses a dynamic characteristic and efficient rapid power exchange with the existing grid in conditions where there are small and large perturbations for mitigating instabilities [153]. This may be reflected in the manner in which the storage technology can control the output power of the connected DG to enhance the stability of the electrical power system. The use of SEST is likely to be prominent in the future for balancing voltage deviations in and operation of active DNs.

The recent trend and progress in artificial intelligence (AI) approaches are attracting increasing interest in design and analysis purposes in engineering disciplines, including renewable energy technologies, DERs, and smart grid infrastructure applications. Recent studies have demonstrated the capability of AI techniques in examining grid-integration problems, which is expected to be commonplace in future research parlance. As it has already been established that the instability experienced in DNs as a result of on-grid DG or microgrid systems requires effective and well-coordinated control mechanisms. The authors in [19] have provided an insight into the AI-based technique for achieving desirable deployments of DG systems in DNs using the case of AI-based human-robot for cooperative control of microgrid in DNs. This way, future research focus will likely consider the technical case of integrating distributed generation with distributed intelligence (DI), i.e. DG plus DI [166]**.** This will benefit from well-managed architecture and operation.

Smart grid (SG) continues to gain popularity in electrical power and energy management parlance because of its exciting features and advantages. SG is essentially a technology that is designed to achieve a maximum benefit of utilities and the users to provide an economic and reliable electrical supply through efficient utilization of available resources and smart tools [167]**.** The key elements of SG are efficiency and reliability, demand response, integration of renewable energy technologies, and integration of electric vehicles [168]**.** These, and the self-healing property of SG that seeks to achieve reliable, fault-tolerant, and resilient operation of the power system will motivate research on grid-integration issues. It is expected, therefore, that future research on distributed generation will be conducted with the consideration of an intelligent grid compared to a case of conventional networks. It is pertinent, therefore, for researchers to further explore the possibility of introducing intelligent tools or devices on the traditional grid in manners that will help address the issue of active power curtailment and voltage deviation towards achieving the desired sustainable power grid. This will include the design and analytical considerations to ensure that the DN and DGs are fully explored.

It is also important for future research to consider both the asset and grid control to properly dissect the impact of deploying large-scale distributed generation on the power distribution grid. From the point of view of asset control, the utility cannot own or approve distributed generation in all cases, while under the scope of grid control, the growth of small-scale DG that present significant cumulative effect whose operation is possibly not directly managed by the grid operator or the utility could pose challenges to the grid [169] This aspect is associated with sound techno-economic analysis as one common goal of the end-users by investing in a grid-tie solar PV system, for instance is the reduction of the monthly bill. However, there is the technical implication of connecting a high percentage of such a system on the grid. A comprehensive analysis is required to deepen the understanding and balance between asset control and grid control, though [169] argued that the size of DG that may be accommodated by a DN is determined by how advanced the network is and how the intended DG has been defined.

Another possible direction for future work is to strengthen intensive and extensive research efforts in the aspect of smart or advanced DC-AC converters. The practical application of such power electronic devices is to ensure suitable grid-interfacing and then manage the voltage profile when DG is integrated by effective VAR coordination and management.

The integration of a high proportion of DG systems may in one way or the other require the reinforcement of the existing DN. This may be in addition to the other voltage control measures. However, it is necessary to ascertain how to minimize the cost of constructing and operating new feeders and sub-stations. Research studies may be intensified in this aspect. Besides, while an active network is prominent in developed countries, it does not exist in several developing countries around the world. This gap suggests the need to emphasize and coordinate future grid research studies for developing countries. Currently, the application of grid-independent microgrid systems is the trend in developing countries as a means to make-up for the poor and inefficient centralized grid system. Future studies need to be strengthened towards the on-grid application of microgrid systems in developing countries.

Several future research directions have also been suggested in [44] with a focus on the crucial and extensive research efforts that are necessary to implement evolving active DNs for flexible and smart operation, control and management. These efforts will be needed in the following 8 research aspects: wide-area active control, adaptive protection and control, network management devices, real-time network simulation, advanced sensors and measurements, distributed pervasive communication, knowledge-extraction by smart methods, and novel transmission and distribution systems design. Strengthening research capability in the mentioned areas will add value to the body of knowledge.

6. CONCLUSION

This paper has discussed the issue of the voltage rise problem and its impact on distribution networks with high penetration of distributed energy resources (DERs). It has presented different DG technologies such as those based on conventional and unconventional resources, and other DERs. It presented conventional technologies such as internal combustion engines (ICEs) such as reciprocating and diesel power systems and the external combustion engines (ECEs) such as the Stirling engines. The unconventional DG technologies that have been discussed include solar, wind, small hydro, and biomass systems, while the other DERs are the battery storage and the fuel cells systems.

The study provided a comprehensive overview of approaches employed to curtail the issue of voltage increase at the point of common coupling (PCC), which include the strategies that are based on the network reinforcement methodology and the active distribution network management. The category of grid reinforcements includes the options to install auto-transformers on the feeder, adjust primary substation and distribution transformer tap setting, install common DC link in domestic LV system and upgrade the conductors to reduce impedance. However, network augmentation methods are relatively expensive due to the cost of infrastructural changes and the installation of equipment.

The active network management, on the other hand, is less expensive and has been effective at curtailing voltage rise issues as well as allowing more DGs to be connected in the distribution networks. The methods include the use of voltage/VAR control devices, active power curtailment, the use of load control, energy storage system, reactive power compensation devices, and DG reactive power management. These methods have been deployed in cooperatively to achieve satisfactory results on the distribution network.

Selecting the most economical solution(s) is not straightforward. It involves considering the network profile involved, the distribution energy source, and agreement with the DNO to prevent a conflicting operation in the existing schemes on the network. With the modern architecture of a centralized and distributed voltage control scheme, the advancement in digital technology to support and aid communications among controllers as well as the capability of advanced metering infrastructure (AMI) to collect and send control signals, the future smart grid in the context of distribution generation will be able to solve the voltage rise issue by the integration of various voltage control methodologies in a real-time manner. This will allow higher penetration of distributed resources in the network without violating the permissible voltage limit. A techno-economic comparison has been introduced in the paper to ascertain the similarities and dissimilarities of different mitigation approaches based on the technology involved, ease of deployment, cost implication, and their pros and cons. Voltage increase as a result of integrating a low-proportion of DG systems to the existing network may not constitute a voltage problem if it does not exceed the allowable value of voltage rise, i.e. the set limit, at the PCC and the surrounding section of the network. However, the specified limit is usually exceeded when a high percentage of DG is integrated, which can lead to overvoltage. The unhealthy effect of overvoltage, including the bi-directional power flow, power quality, exceeding of thermal limits and instability issues in the network require the use of effective mitigation and control strategies when integrating a high percentage of DG technologies with the existing grid. The paper provided insights into directions for future research in mitigating the impact of voltage rise presented by grid-connected DGs without limiting their increased penetration in the existing power grid.

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