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A Review of Voltage Control Methods in Conventional and Active Distribution Network

Oladepo, O., Lasisi, H. and Awofolaju, T.T.

Abstract: The rapid expansion in electrical power demand and challenges in providing required capacity using conventional solutions, such as network expansions and substation upgrades, motivates the selection of distributed generation (DG) option. The DG are complementarily combined based on their renewable sources, to form a microgrid for real and reactive power support. However, there is a need for proper coordination to smoothly coexist with conventional devices on the power network. The significant benefits of the integration include improved voltage profile and power loss reduction. In this article, the DN and active distribution network (ADN) are briefly introduced. Then the voltage control techniques in both passive and ADNs were reviewed. The existing literature is outlined as a potential guide for researchers in the field. The literature reveals that the coordinated voltage control involving the combination of voltage control devices and methods proved effective than standalone methods.

Keywords: Voltage control, Distribution network, Renewable energy sources, Distributed generation, Active distribution network

I. Introduction

Active distribution systems (ADSs) are networks with a system in place to control the combination of distributed energy resources (DER). The integration of renewable energy sources (RESs) in distribution systems (DSs) is more pronounced in modernized power distribution architecture. The trend is envisaged to continue due to the general reduction in environmental pollution and depletion in fossil fuel [1]. However, the distribution network had experienced a paradigm shift from passive to an active network, as the power flow and voltage profile is being determined by intermittent renewable energy sources and loading conditions [2], [3].

Oladepo, O., Lasisi, H. and Awofolaju, T.T
(Department of Electrical and Electronic Engineering, Osun State University, Nigeria.)
Corresponding Author: ooladepo@yahoo.com,
Phone Number +2347035665642

Consequently, the network operators are faced with challenges of voltage fluctuation, protection and network overloading, among which the fundamental problem lies in voltage variation beyond the statutory limit. Therefore, the increasing penetration of RESs in power distribution networks brings additional uncertainly, instability and strain to the system. Given the above, there is a need for a strategic performance evaluation to come with an efficient voltage control strategy for voltage delivery within the operation limit [4].

Novel and efficient management of DSs operation, coordinated control of smart applications and coexisting renewable generators with conventional electrical equipment cannot be over-emphasized. Hence, taking advantage of the microgrid (MG) concept for the effective utilization of active distribution networks (ADNs) is highly imperative [5]. It implies that new control applications and strategies are required to ensure efficient operation of DSs.

II. Distribution System

The distribution system is an essential power link between centralized generation equipment and vastly distributed end-users. Its architecture commences with the distribution substation that is directly fed through one or more sub-transmission lines [6]. The high-voltage transmission system transports an enormous amount of electrical energy at high voltage to accommodate line losses.

The DS serves areas on a small scale by branching and continuously lowering the voltage to appropriate values for consumer loads. With rare exceptions, feeders are radial, meaning that the flow of power is unidirectional, from its substation to the users [7]. However, the feeder could be configured either in an open or close loop structure. It is the most significant and vital subsystem of the power system that shows the performance indices of power delivery [8].

The network designed is based on technical requirements such as peak load, maximum fault current, voltage and some other conditions like terrain, visual regulation and customer needs. The reactance to resistance ratio on the distribution network is low compare to what obtainable in the transmission network, hence the power quality compensating devices are selected carefully to keep power delivery within the operating limit [9]. The power industry has experienced transformative innovation toward distribution automation and the integration of alternative energy sources [10]. It is due to the passiveness of the distribution network, high variability in the load profile (predominantly home electrical loads), decentralization of power sector and the need for alternative energy sources.

A. Active Distribution Network (ADN)

Electrical networks are experiencing a significant transition from a passive distribution network (PDNs) into ADNs. A unidirectional flow to bidirectional power flow. DNs without the integration of DG units are passive since the power is only supplied from the centralized grid to end-users. It only becomes active when DG is integrated [11]. It is an efficient DNs management strategy on the condition of the high integration of DG [12].

However, ADNs need to accommodate distributed intelligent control systems to harness energy from renewable DERs and MG network. The concept of ADNs is regarded as a significant solution to achieve power sustainability and energy production security. Currently, it is an inevitable trend to exploit the full use of renewable DGs like small hydropower and photovoltaic (PV) units [13, 14].

Intelligent ADNs have become accepted in power sectors all over the world for its immense technical and environmental contributions. This includes customer expectations of qualitative power delivery, emerging power policy accommodating renewable DERs with energy storage system (ESS), reduction of carbon emission by 50% by 2050 and motivation on distribution network operators (DNOs) for smart asset utilization [11].

Modern ADNs planning considers probabilistic methods to capture RESs and other uncertainties. However, the application of probabilistic techniques makes network studies more sophisticated with its associated errors. Some DNOs still adopt the conventional

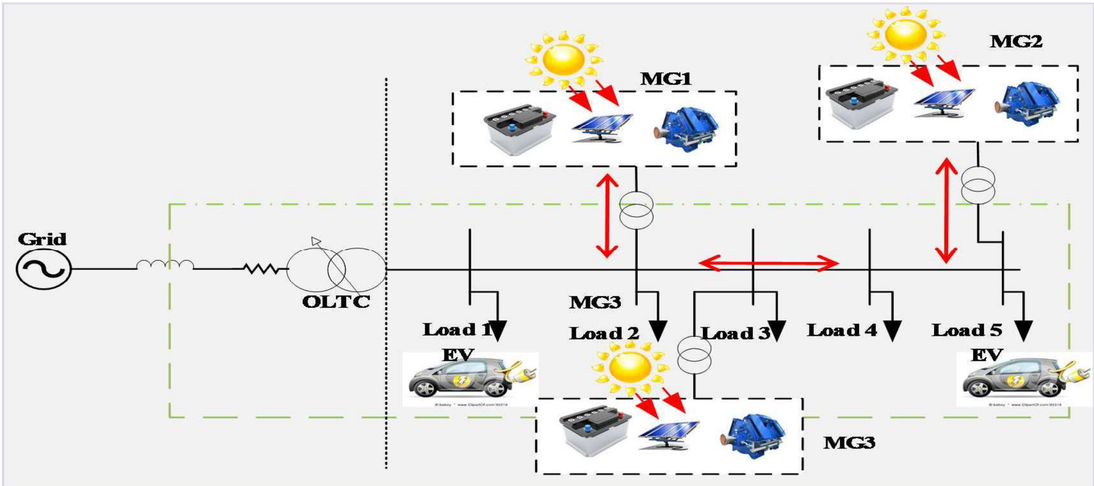

Figure 1: Active distribution network with three micro grids

deterministic methods. However, it is proven ineffective as the level of uncertainties increased.

The effectiveness of a control strategy is a significant factor to be considered in ADNs with frequently changing power output couple with time delay associated with automatic voltage controller. Some researchers adopt a fully centralized control method. However, improper coordination of voltage control devices, non-instantaneous data processing and conflict of control mechanism leading to the exclusion of devices at the terminal end of the network are the challenges [15].

Besides, ADNs are challenged with the reverse flow of power, flow in the transmission system, line overload and congestions. The dynamic technical challenges include reduced system stiffness and power system instability [16]. Figure 1 shows the ADN with bidirectional power flow in the presence of DER, electric vehicle (EV), load and MG.

III. Conventional Voltage Control Methods

In traditional DNs, the DNO manages the network by operating the DG at unity or constant power factor. The method limits the installed capacity of DG and proved ineffectiveness in ADNs [17]. Other voltage control approach used in the traditional network includes on-load tap changers (OLTCs), voltage regulators, fixed capacitor and inductor. These components are not entirely applicable to ADNs due to several limitations in adaptability to the active networks such as slow response time, switching arching, tap short-circuiting and over/under compensation during variable load with high integration of DG [18]. Therefore, the challenges motivated the modification of a conventional configuration of components to accommodate variable loading conditions in the presence of renewable generations (RGs) [19].

A. On-Load Tap Changing Transformer (OLTC)

OLTCs is used to regulate voltage magnitude at the load tap changing terminals by adjusting its transformation ratio. It possesses the dual function of energy transformation in different voltage magnitude and phase control [20]. However, earlier load tap changer (OLTC) had considerable setbacks like arcing, coil short-circuiting, high maintenance rate and service cost [21]. In 1926, the reactor under load tap was invented and presented in [22]. The reactor tap was later replaced by resistor tap changer, which eventually transformed to electronically assisted OLTC using solid-state power switches such as a thyristor, triac and insulated gate bipolar transistor.

In [23], the author presented a single-phase tap changer using gate turn over (GTO) with an anti-parallel thyristor to perform upward or downward switching of voltage using transformation ratio. In [24], the author proposed a solid-state voltage regulator using a solid-state tap change mechanism for distributing transformer. The study employed pulse width modulated techniques for sequential switching. However, the challenges associated with delay, accompany harmonic and ripples when switching from one tap to others had not been wholly isolated [25]. Therefore, the combination of OLTCs and other power control devices proves more efficient in providing voltage control.

In [26], a combination of OLTC with static var compensator (SVC) was proposed for voltage magnitude correction and reactive power compensation. With the increasing potential of RESs in modern DSs, coordinated control of OLTC with local wind power generator was implemented in [27] and with PV in [28]. However, wind and PV generators are highly intermittent with low inertia. Therefore the addition of local control mechanisms and adaptive controllers play a vital link between OLTC and DG. An area-based approach was used in [29] in which voltage information of different buses is used to determine the best tap position to minimize the voltage drop. However, regulating a voltage level at the remote bus through a communication link could greatly be affected by the actual location of the regulating device. Hence, a holistic, coordinated control combining the local and centralized scheme that establishes an adaptive link between conventional methods and RESs forms a better option for ADNs. Figure 2 presents the OLTC voltage compensation scheme

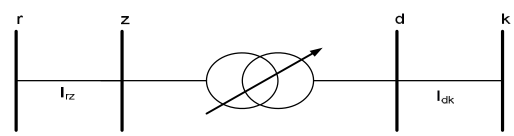

Figure 2: OLTC voltage compensation scheme

The transformer tap range is mostly ± 10% of transformer rated voltage while numbers of taps determine the step voltage. The sending end voltage in respect to receiving end voltage is expressed as

$$[V_d]_{abc} = [n_R]_{abc}[V_z]_{abc} \tag{1}$$

$$[I_d]_{abc} = \left[\frac{1}{n_R}\right]_{abc} [I_Z]_{abc} \tag{2}$$

where n denotes effective turn's ratio of the regulators and

$$n_R = 1 \pm tap(\Delta V_T) \tag{3}$$

where ΔV_T is the tap change step. The '+' sign in (3) implies a raised tap and the '–'sign is for the lowered position.

B. Capacitor Banks (CBs)

Capacitors are frequently used to correct the power factor of lagging loads for loss reduction and voltage boosting. It is used as shunt capacitors to augment line capacitance. It is a reactive load generator under heavy loading conditions, while series capacitors are used for line length compensation [25], [30]. In three-phase wye connected shunt capacitor bank, the individual phase capacitor units are specified in kVar and kV to computes the susceptance (in Siemens) of a capacitor unit as:

$$B_c = \frac{k\,\text{var}}{kV_{LN}^2.1000} S \tag{4}$$

kVar denotes voltage reactive power and kV^2_{LN} is the terminal voltage between the line to neutral. The capacitance depending on the network reactive power requirement, is expressed as:

$$C = \frac{Q}{2\pi f * V^2} \tag{5}$$

The reactive power Q is a variable, a function of network loading condition which needs to be determined dynamically to make a correct value of compensation and increment required. CBs present some advantages: power quality improvement due to improved power factor, reduction in thermal losses and an increase in network capacity. However, CBs are not a smart dynamic reactive source when an active state of the network is considered due to the generation of switching transients [31]. Also, injected power by capacitor might drop at low feeder voltage because it varies directly with a square of voltage [32].

The traditional fashion of capacitors was of fixed capacity, which was manually switched based on the network on/off-peak load condition and cannot regulate rapidly changing reactive power requirements on ADNs [33], [34]. A fixed and manually switched CB can often result in either under or overcompensation [18]. The impact of CB on power factor improvement in aluminium production power networks was presented in [30]. A power factor improvement from 0.89 to 0.95 was recorded, however reactive power compensation as a function of time (adaptive technique) was not considered. In [35], power factor improvement using CB under variable load was proposed. However, the performance analysis was not on a standard distribution network. It only has three points of load values with three levels of varying CB compensators.

IV. Voltage Control in Active Distribution Network

Conventional voltage control devices operate based on voltage drop along the feeder of the network, from the source to the end node. Modern active devices such as ESS, DG and EV constitute an integral part of voltage control devices in active distribution operation mode.

A. Centralized Voltage Control

In a centralized voltage control method, the central coordinating unit takes the control decision on voltage regulation. The real-time information about the voltage level at each point of common connection (PCC) is supply to the central unit through a communication channel [36]. The voltage data is being analyzed by the central management system, where a control action is initiated and send to remote equipment for necessary voltage regulation [37]. Supervisory control and data acquisition (SCADA) systems often provide a communication link. However, the SCADA system is hardly available at the distribution network.

Consequently, only data from primary substation measurements can be available at the distribution level. The voltage level along the radial network nodes at the distribution network has to be determined through the estimated method. Therefore, the method is not directly used at the distribution level [33]. Besides, sensors, communication equipment with control systems require high investment costs. Every node needs to be installed with communication facilities, which may not be practically realizable. Also, the centralized method depends on a central computer to initiate a control action that can lead to delay time in data processing and subsequent single point of failure [38]. A distributed approach is advantageous in this respect in that failure of one bus only affects a localized section of the DN.

B. Decentralized Control Method

In view of the limitation in centralized control in the distribution system, decentralized approaches had been proposed in voltage control for ADNs [17]. It uses local voltage swing, sensitivity, and a combination of localized voltage control techniques. Prominent among the decentralized method in ADNs is a multi-agent system (MAS) technique [39]. In MAS, DNs are divided into sub-networks. The sub-unit agent is responsible for managing the voltage profile in its jurisdiction. The sub-network agent takes control action base on local measurement and local control algorithm [40]. However, in contrast to the centralized method, the optimal global value cannot be guaranteed as the decision of each agent may produce conflicting results without a point of convergence [17].

C. Optimization of Distributed Generation

Metaheuristic methods are defined as upper-level general methodologies applicable as guiding strategies in modeling and formulation of underlying heuristics to solve optimization problems [41]. They are intended to extend the scope of heuristics by combining one or more heuristic methods, a procedure for high-level strategy. The method involves a minimization or maximization of the objective function for best DG sizing and placement. It could be either an experience-based technique or a higher-level technique without requiring training in searching for the iterative optimal solution. The methods are robust and produce a near-optimal solution for large, complex optimal DG allocation problems. Prominent among the complimentarily combined distributed generators are solar generator, wind and small hydropower.

i. Solar Photovoltaic (PV)

The photovoltaic system is weather dependent and imposes technical challenges such as power fluctuation and instability [42]. Some researchers adopted a demand-side response [43]. However, the method shifted part of network control over to the end-users, which might be dangerous when there is a need for DNO emergent decisions on the network. Other researchers proposed day-ahead programming. However, it is susceptible to error because electrical power demand is not static. It is dynamic with an instant of time, weather and season.

Other methods include the use of ESS and complementary combination of RESs. However, the use of ESS demand proper sizing, placement and efficient coordination. PV control approach using maximum power point tracking (MPPT) has been prevalent in PV systems. Many of the MPPT algorithms are limited due to slow tracking and reduced efficiency [44]. Researchers in the literature widely use incremental conductance (INC), perturbation and observation (P&O) or hill climbing. However, the operating point in the P&O method oscillates around the maximum power point (MPP), resulting in energy loss. It is not also suitable for frequently changing scenarios [45]. INC method offers good output under rapidly changing weather. It also has lower oscillation around MPP comparing to P&O. Besides, INC is usually proposed for adaptive variation in voltage step base on the PV curve [46]. The capacitor bank compensates for the reactive component of the grid, while the MPPT technique regulates the active power flow [47]. Hence, the simultaneous achievement of real and reactive power control.

ii. Small Hydro-Power Plant (SHP)

SHP can mimic the stability and high inertia of a conventional centralized hydro generator with the usage of a synchronous machine. It is of high efficiency and capacity factor with a reduced rate of fluctuation compare to solar and wind [48], [49]. However, for a better performance against voltage instability, the system is better corroborated with a means of control. The excitation control system plays a paramount impact on the dynamic stability of the power network [50]. Most of the recent researchers focused on the use of ESS back up as voltage support for SHP [51]. In [52], dynamic voltage restorer based on PV source was combined with SHP for voltage regulation. However, flexible alternating current transmission systems (FACTS) are costly and not readily available in most developing countries. The combination of PV and SHP was considered in [53], but there was an exclusion of local means of control in both PV and SHP configurations, which could have provided the basis for better performance in voltage regulation and power balance.

D. Demand Side Management (DSM)

DSM permits the end-users an active role in distribution network management. The end-users are motivated to shift their load demand to the off-peak time to reduce maximum total load demand. This technique reinforced network reliability and stability for optimal efficiency. In the review presented by [54], the DSM suffers from externality challenges which involve the impact of high-level consumer consumption on the price determinant of other customers mostly at peak period.

E. Coordination of Energy Storage System (ESS)

ESS can efficiently equalize network fluctuations and compensate for a power mismatch between generation and load demand through a coordinated time-series power supply and energy shift [55]. It carries a significant role in DNs for providing energy supply during power intermittency when RGs are involved [56]. ESS is modeled as a load that absorbs power (charge) or a generator that injects power (discharge) within its energy stored capacity and its power capacity (P_{rated}). ESS devices make use of a power conversion system for power connection in DN. The location of the ESS in the power network plays a significant role by enabling the excess to be stored locally with less line loss and then re-dispatched to the same node when required.

V. Conclusion

Necessity is the mother of all inventions; the idea to move power grid to an active distribution network is born out of increasing power demand, depletion in fossil fuel, need for power liberalization, and insufficient centralized power generation among others. However, there are various technical challenges such as intermittency, network fluctuation and bidirectional flow. These technical challenges motivate the authors to focus on previous research on different voltage control strategies in conventional and active distribution networks.

Most of the techniques discussed have their strengths and deficiencies. It is therefore not advisable to use a voltage control method as a standalone scheme, a complementary combination of methods under a well-defined coordinated strategy offers a better solution. It is strongly believed that the review will serve as a guide for future researchers.

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