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Review of control strategies for voltage regulation of the smart distribution network with high penetration of renewable distributed generation

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ABSTRACT

Integration of renewable energy sources (RES) into traditional power system is one of the most viable technologies to meet the ever increasing energy demand efficiently. But, this technology arises a lot of challenges which are necessary to be taken care of for smooth operation of the network. Voltage regulation is the most significant technical challenge that tends to limit the amount of penetration of renewable distribution generators (DGs) into the distribution network. This paper attempts to present a detailed review of the control strategies that are being utilized to mitigate voltage regulation challenges when increased amount of renewable DGs are connected within the distribution network. This study analyses the direct impacts of increased accommodation of renewable DGs on the distribution network operation and evaluates current research status of voltage control strategies. Then qualitative analysis is performed for all kinds of voltage control approaches involving their pros and cons for the first time. The objective of this contribution is to present the latest research status of distribution system voltage control strategies with highly penetrated renewable DGs and a brief review of different control methodologies.

Contents

1. Introduction

The incorporation of RES in electric power system is being popular day by day. Previously, it was mostly off grid connection. But nowadays, grid connected RES are coming into trend. Integration of

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Nomenclature

RES	Renewable energy sources
DG	Distribution generators
PV	Photovoltaic
DNO	Distribution network operators
PSS/E	Power System Simulator for Engineering
DN	Distribution network
OLTC	On-load tap changer
DSSE	Distribution system state estimation
SC	Switched capacitor
SVR	Step voltage regulator
ANM	Active network management
SCADA	Supervisory control and data acquisition
STATCOM	Static synchronous compensator
FACTs	Flexible AC Transmission System
CBA	Cost benefit analysis

RES into power distribution system was not any serious issue a few years ago as the amount of penetration wasn't that much significant. But currently, a large amount of renewable energy sources are being connected which are posing a lot of impacts on the operation and protection of the distribution network [1–3].

The characteristics of the power distribution network are different from power transmission network in several ways. They are as follows [4]:

- It works in radial topology.
- There can be significant unbalance.
- The R/X ratio of the distribution network is relatively higher than the transmission network.

For the planning and stable operation of smart distribution infrastructure, it is necessary to analyse the relation between the integration of renewable DGs and the distribution network's behavior [5]. As DGs are connected very near to customers, connecting them has significant effects on distribution network's technology, environment and economy as well as customers [6–8]. Integration of DGs in the distribution networks is not yet problem free. The traditional grids were designed to supply the electric power from generation side to customer's loads. According to this design, the electric power flow was supposed to be unidirectional (from higher to lower voltage level) through the whole system. But, when we integrate DGs in the distribution network, the excess power generated by DGs after meeting the customer's demand, flow back to the generation side. So, the power flow remains no longer unidirectional. It is rather bi-directional which has significant adverse effect on the operation, voltage regulation and protection of the power distribution network [6,9,10].

Several efforts have been made to review the stability issues, operations and control technologies of the power system when large-scale DGs are interconnected [11–15]. Refs. [11,12] have discussed about different control strategies and stability issues in a systematic structure but they mainly focused on micro grids. Refs. [13,14] have done extensive reviews on the power quality issues, reactive power management and voltage management where several control devices and methods have been discussed and relative comparisons of their performances have been presented. But, systematic classifications of voltage control structures according to respective functionalities have not been discussed. Ref. [15] investigates some low-voltage ride-through enhancement methods during voltage dips and inter-area oscillation damping techniques for wind and photovoltaic power plants. But, control schemes for real time voltage regulation during system operation was not widely discussed.

This paper mainly focuses on the voltage regulation challenges raised from increased renewable DG interconnection with low-voltage distribution networks and detailed review of voltage control strategies to mitigate its adverse impacts on voltage profile. Existing control methodologies have been classified into centralized, decentralized autonomous and decentralized coordinated control structures according to their respective functionalities. Then qualitative analysis is performed among these classes involving their advantages and disadvantages. This paper is organized as follows. Section 2 describes the challenges that arise due to increased DG accommodation. Section 3 details the impacts of large-scale DG connection on the voltage profile of the network. Section 4 analyses several traditional and advanced voltage control methods and different control structures depending on their functionalities. Section 5 establishes the conclusion derived from the work.

2. Challenges of increased penetration of DGs in distribution network

The challenges that occur due to increased penetration of DGs in distribution networks can be classified into three categories [3].

1) Technical challenges.
2) Commercial challenges.
3) Regulatory challenges.

These challenges are going to be discussed in brief.

2.1. Technical challenges

2.1.1. Power quality

Depending on the particular circumstance, connecting DGs within the distribution network can either deteriorate or improve power quality [16–18]. DGs are connected closer to the loads and most of the loads are supplied by DGs in case of higher penetration. As a result, lesser amount of power is drawn from the distribution substation. So, the amount of current flow from the distribution substation to the consumer's loads through the feeder and its laterals is reduced. So does the power loss through the feeder [16]. But, there are other two important aspects of power quality. They are:

- Transient voltage variation.
- Harmonic distortion of the network voltage.

Single large DGs may cause power quality problems in a weak distribution network particularly during starting and stopping.

2.1.2. Protection

The protection of the distribution network due to integration of DGs is affected in several ways [19].

- Changes in the traditional distribution network short circuit power.
- Changes in fault current level.
- Changes in the characteristics of the fault current, such as amplitude, direction and distribution.

Most of the distribution networks were designed and built considering unidirectional power flow (without DG). So, during a fault the protection relays cannot coordinate among themselves properly in a radial distribution network when a significant amount of DGs are connected and Bi-directional power flow occurs [20,21].

2.1.3. Voltage regulation

Voltage regulation issues due to high penetration of DGs are one of the key issues that limit the integration of DGs in the network. Due to bi-directional flow of power, regulating the voltage through the distribution feeder needs more advanced strategy [5,6,9,10].

2.1.4. Stability

In case of conventional passive distribution networks, stability is not any significant considerable issue. Day by day the penetration of DGs is increasing. As a result, the stability of the smart distribution network should be a significant consideration. Researchers tried to figure out the maximum amount of DGs that can be penetrated into a particular distribution network. But this approach was not welcomed by the DG manufacturers [22].

Effects of large amount of DGs penetrated into the distribution network depend on several parameters [23],

1. The voltage level of the feeder where the DG is connected.
2. Category of the distribution network.
3. The amount of customer demand.
4. The percentage of penetration.

Depending on these parameters, integration of DGs has significant effect on voltage profile, network losses and fault level [24–27]. For most of the distribution networks, they are radial and power flows from higher voltage level to lower voltage level. The resistance to reactance ratio (R/X) is more than one for distribution network and less than one for transmission network. Due to higher resistance, the voltage drop is higher in the distribution feeder. On the other hand, due to higher values of R/X, the impact of the real power provided by DGs has more influence on voltage profile than the impact of reactive power [28].

2.2. Commercial challenges

If proper active management can be applied, the benefit of integrating large-scale renewable DGs in the distribution network is expected to be greater than the installation cost. But, for that, developed commercial arrangements are necessary. A well-designed incentive scheme can be stablished that can encourage the companies to apply active management on grid-connected renewable DG networks. On the other hand, implementation cost of proper active management and the incentives can put effect on the electricity price for the consumers.

2.3. Regulatory challenges

Low voltage distribution networks were designed to deliver power unidirectionally from generation to grid. But, it does not remain as a passive network any longer when large-scale renewable DGs are interconnected. To operate the large-scale DG connected distribution systems properly, appropriate regulatory policies need to be developed those ensure smooth and uninterrupted operation of the system.

3. Impact on voltage regulation of distribution network

Voltage regulation issue has been considered as the most vital issue for integration of large amount of distributed generators (DGs) into low and medium voltage distribution networks [28–30]. Several researches have been done to mathematically describe the impact of large scale renewable DGs on the voltage profile of distribution network [5,31,32]. A brief discussion about the impact on voltage regulation of distribution network is as flows.

Let's consider a simple conventional two bus distribution system.

In Fig. 1(a), we can observe a two bus conventional distribution feeder. V_s stands for sending end voltage, V_R stands for receiving end voltage. R represents the resistance and X represents the reactance of the distribution feeder. DS stands for the distribution substation; OLTC stands for on-load tap changing transformer. P and Q are the active and reactive power flowing through the feeder. P_L and Q_L are the active and reactive power consumed by the load respectively. In Fig. 1(b), a DG has been connected with the conventional simple feeder. After connecting DG in the distribution feeder, there is a voltage rise at receiving end (DG bus). Let's consider the increased voltage at the bus where DG is connected is $V_{g.}$ The active and reactive powers generated by the DG are P_g and Q_g respectively.

From figure (b), we can write the DG bus voltage as,

$$\hat{V}_g = \hat{V}_S + \hat{I}(R + jX) \tag{1}$$

where $\hat{V}_g$, $\hat{V}_S$ and $\hat{I}$ represent the corresponding phasor quantities of DG bus voltage, sending end voltage and current flowing through distribution network respectively. Power flowing through the feeder can be written as,

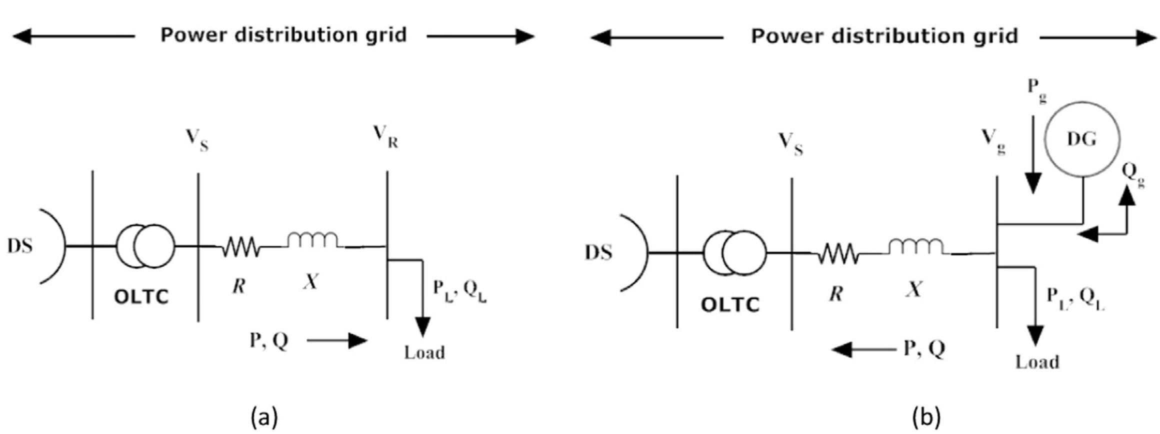

Fig. 1. (a) Conventional simple distribution feeder, and (b) simple distribution feeder with DG.

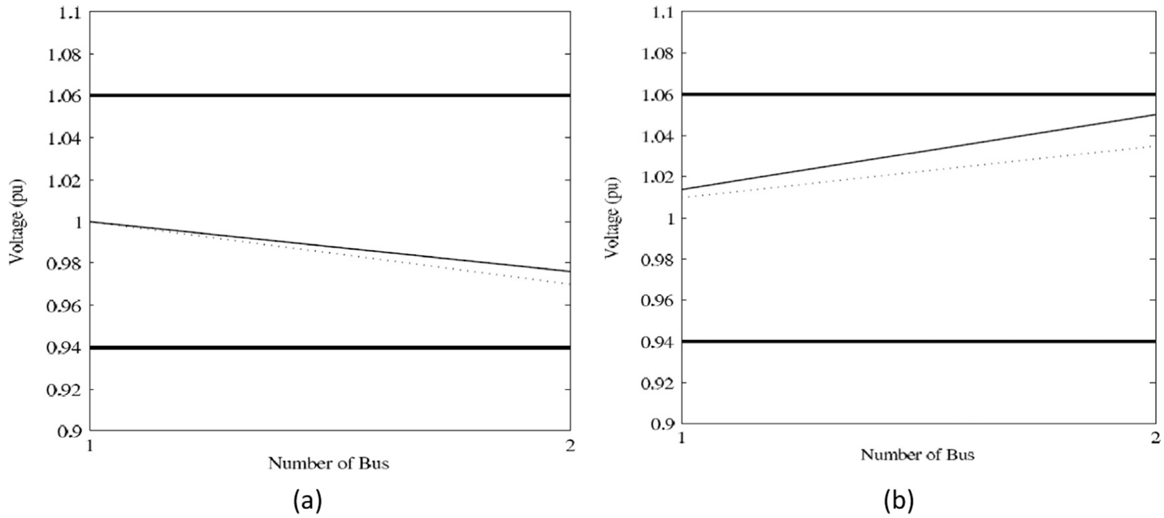

Fig. 2. (a) Voltage deviation along the feeder in a conventional two bus distribution system, and (b) voltage deviation along the feeder in a DG connected distribution system. The solid line represents the result obtained from PSS/E; the dotted line represents the result obtained from derived formula. Two bold solid lines indicate the permissible range of voltage variation [33].

$P + jQ = \widehat{V_g} \cdot \widehat{I^*}$.

So, the current flowing through the feeder,

$$\hat{I} = \frac{P - jQ}{\hat{V}_g^*}$$

So, Eq. (1) can be expressed as,

$$\widehat{V_g} = \widehat{V_S} + \frac{P - jQ}{\widehat{V_g^*}}(R + jX) \tag{2}$$

$$= \hat{V}_S + \frac{RP + XQ}{\hat{V}_g^*} + j\frac{XP - RQ}{\hat{V}_g^*} \tag{3}$$

The voltage drop across the feeder is approximately equal to the real part of the voltage drop as the angle between the DG bus voltage and the sending end voltage is very small. If we consider the DG bus voltage as reference bus, the angle of DG bus voltage is 0. As a result, Eq. (3) can be approximated as,

$$\Delta V \approx V_g - V_S \approx \frac{RP + XQ}{V_g} \tag{4}$$

where, ΔV= voltage drop along the distribution feeder.

If we consider the DG bus voltage as the base voltage, we can assume V_g as unity. So, Eq. (4) can be written as follows,

$$\Delta V \approx V_g - V_S \approx RP + XQ \tag{5}$$

where, $P = \left(P_g - P_L\right)$ and $Q = (\pm Q_g - Q_L)$.

So, Eq. (5) can be written as,

$$V_g \approx V_S + R\left(P_g - P_L\right) + X(\pm Q_g - Q_L) \tag{6}$$

From this equation, we can find the amount of maximum permissible DG in distribution feeder that can be accommodated. The worst case scenarios are (considering unity power factor):

1) Maximum generation minimum load ($P_g = P_{gmax}$, $P_L = 0$, $Q_L = 0$)
2) Maximum load minimum generation ($P_g = 0$, $Q_g = 0$, $P_L = P_{Lmax}$)

For the first scenario, considering unity power factor, Eq. (6) becomes,

$$V_g \approx V_S + RP_{gmax}$$

$$\text{Or,} \quad P_{gmax} \approx \frac{V_g - V_S}{R}$$

Let's consider, V_{gmax} is the maximum voltage at the generation bus within the permissible voltage limit along the feeder. So, to keep the voltage within permissible limit, P_{gmax} needs to be,

$$P_{gmax} \le \frac{V_{gmax} - V_S}{R} \tag{7}$$

For the second case also, considering unity power factor, (6) becomes,

$$V_g \approx V_S - RP_{Lmax}$$

$$Or, \quad P_{Lmax} \approx \frac{V_S - V_g}{R}$$

Let's consider, V_{gmin} is the minimum voltage at the generation bus within the permissible voltage limit along the feeder. So, to keep the voltage within permissible limit, P_{Lmax} needs to be,

$$P_{Lmax} \le \frac{V_S - V_{gmin}}{R} \tag{8}$$

P_{Lmax} does not stay within this limit all the time. For larger dynamic load, the bus voltage reduces lesser than the minimum permissible limit.

For the steady state operation, the voltage along the feeder has to be in a permissible limit. There is no internationally applied rule for steady state voltage range along the feeder. For maximum cases, the allowable voltage variation along the feeder is $\pm 6\%$ [19]. Some cases, DNOs set the transformer secondary voltage maximum within permissible limit to ensure that voltage will remain above minimum at the far end of the long distribution feeder.

Let's consider a two bus small distribution system in Fig. 2.

Now, let's consider a large distribution feeder with n number of buses in Fig. 3.

Authors of [33] have simulated an IEEE 34 Node Test Distribution System in PSS/E (Power System Simulator for Engineering) for several percentages of DG integration and the simulation results are presented in Fig. 4.

In order to minimize the adverse effects, distribution network operators prefer to accommodate the DGs at higher voltage level where the impact of the DGs on the voltage profile of distribution feeder is minimal. On the contrary, the developers of DGs prefer to

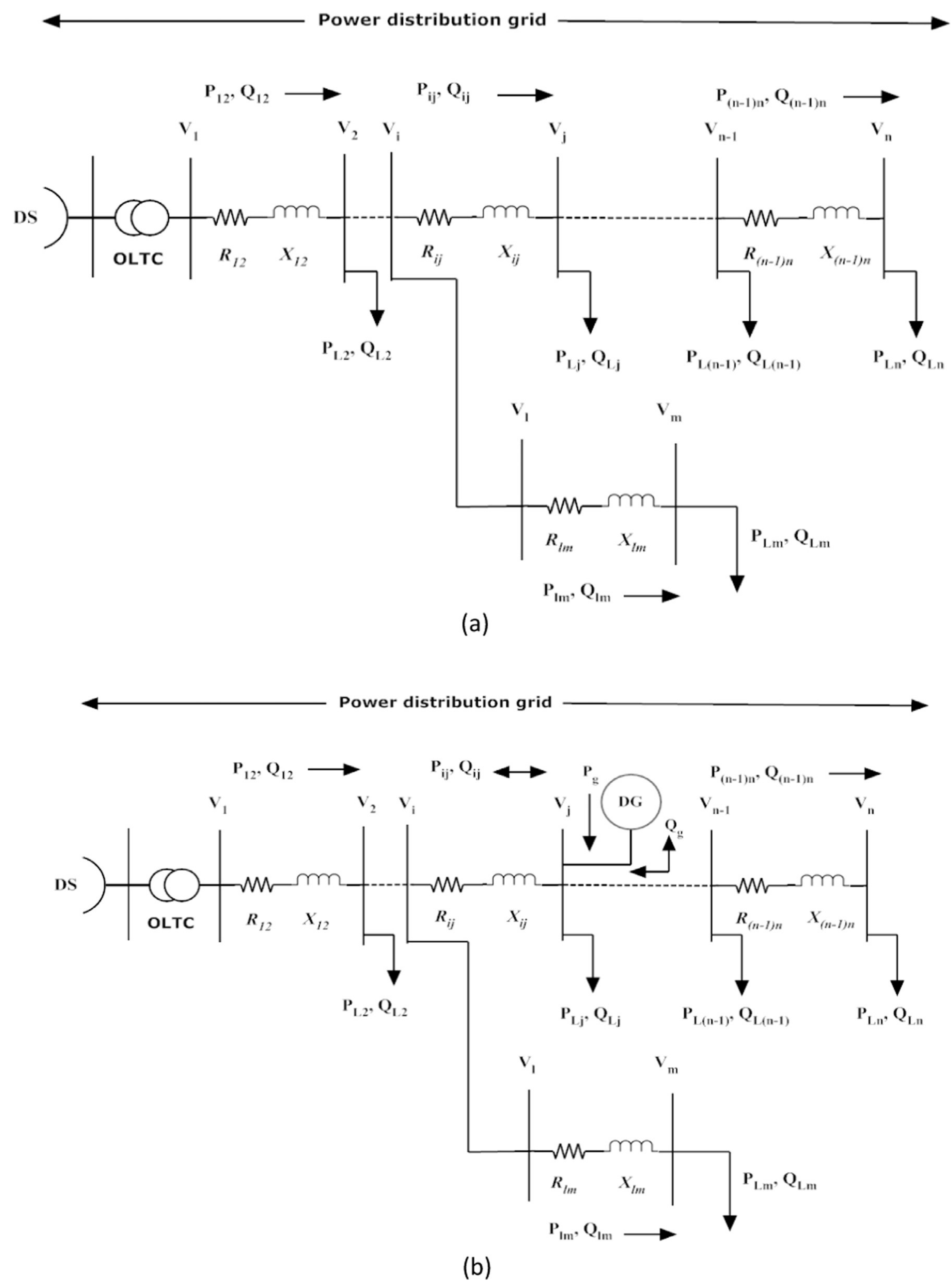

Fig. 3. (a) Conventional n-bus distribution feeder, and (b) n-bus distribution feeder with DG.

accommodate the DGs at the lower voltage level to minimize the connection cost [67,86]. The higher is the voltage level, the higher is the connection cost and vice versa. This conflict of interest can be settled through load flow studies.

4. Qualitative analysis of voltage control strategies

A significant amount of research [34–66] is going on to evaluate the optimum location where DGs should be accommodated and

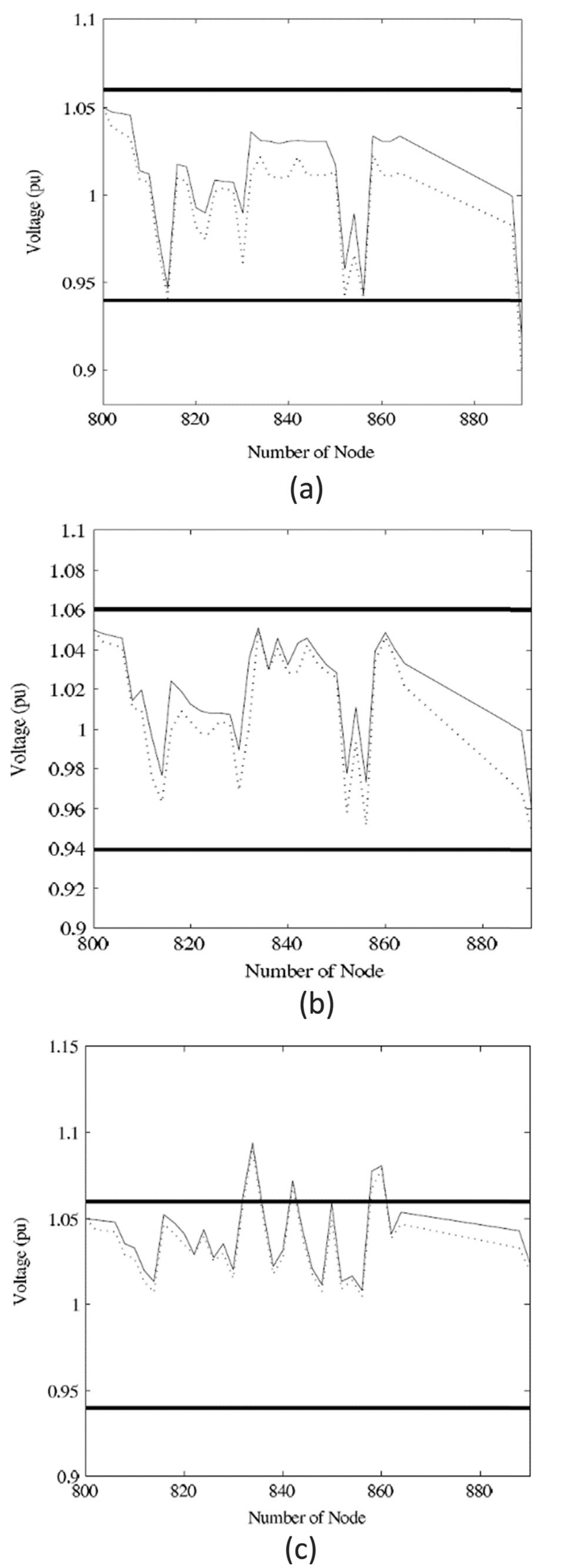

Fig. 4. Simulation results of IEEE 34 Node Test Distribution System with 0% (a), 25% (b) and 50% (c) penetrations of DGs. The solid line represents the result obtained from PSS/E; the dotted line represents the result obtained from derived formula. Two bold solid lines indicate the permissible range of voltage variation [33].

the amount that can be integrated into distribution network. To find the optimal size and location for DG, two kinds of approaches are followed [5]. They are,

1) To accommodate DG's with pre-specified capacities at best locations in the distribution network (DN).
2) To specify network location of interest guiding the DG capacity growth within network limits.

The first approach is done basically by using evolutionary computation. Such as particle swarm optimization (PSO) [34], genetic algorithm (GA) [35–38] and fuzzy logic based methods [39,40]. The second approach is unable to solve continuous function of the capacity. For solving these, gradient search (GS) [41], linear programming [42] or optimal power flow (OPF) [43–48] methods are used. Both of these methods have their advantages and short comings. A hybrid method has been used in [49,50] (where combination of optimal power flow and genetic algorithms and combination of particle swarm optimization & optimal power flow have been used respectively). But they have their limitations too. Some analytical approaches based on the sensitivity analysis have been done in [51–59] to optimally accommodate DGs in the distribution network. Several other different methods have been used for DG optimization and allocation in the distribution network [60–66].

In these methodologies, optimum condition is usually measured by improving the voltage profile. But, unpredictable events like wind gusts, solar radiation excursion or sudden overload may push the node voltages out of permissible limit resulting in cascaded events.

Active network management (ANM), a form of centralized strategy, is proposed as a key to integrate DG units in the distribution network as much as possible. It helps the distribution network operators (DNO) to utilize the maximum use of the existing network circuit by taking several management strategies similar to the transmission system [67,68]. It provides real time monitoring, communication and control of the network by taking the advantages of generation dispatch, OLTC (on load tap changing transformer), voltage regulators, shunt capacitors, reactive power compensation etc.

Another alternative approach proposed to control the voltage within acceptable limits is the intelligent distributed control of DG and other network parameters [69]. There are several different approaches for the distributed control. The effect of integration of DGs on the voltage profile mainly depends on the location of integration in distribution feeder. So, the distribution network configuration should be taken into account while designing the control strategy. Because, same amount of DGs, integrated in different parts of the network, make different impacts.

4.1. Traditional methods

In traditional distribution systems, the voltage regulation is being done usually by,

1) On load tap changer (OLTC).
2) Switched capacitors (SC).
3) Step voltage regulator (SVR).

On load tap changer is a tap changing autotransformer. It adjusts its taps automatically to adjust the voltage by measuring the feeder current at the substation end and estimating the voltage drop along the distribution feeder. Integration of DGs makes the power flow bi-directional and the voltage profile of the network depends on DGs location, injection of active power and power factor of DGs. So, the overall situation through the feeder is unpredictable and uncontrollable by OLTC [22]. Moreover, due to the naturally intermittent renewable DG's varying output and dynamic behavior of loads, the voltage variations occur so rapidly that traditional OLTCs or SCs cannot regulate as fast as they require. Another simple solution is to lower the set point of the OLTC at the substation so that the increased voltage at DG bus remains within upper permissible limit. However, this method is unable to ensure that the voltages of all the network nodes will be within permissible limits throughout the feeder. In addition, other feeders might be connected to the same transformer. Then, this strategy can adversely affect other feeders. Currently, over traditional mechanical OLTCs, new solid state OLTCs are there which are performing better with lesser maintenance cost. They provide significant control capability such as coordinated control with communication [70]. Step voltage regulator (SVR) is also a tap changing automatic voltage regulator that locates along the feeder [71]. A switched capacitor (SC) is an electronic circuit element. It works by moving charges into and out of capacitors when switches are opened and closed.

4.2. Advanced methods

Several alternative methods with different controllable components were evaluated in several literatures to solve the voltage rise mitigation problem. A brief discussion about the controllable components is as follows:

a) **Generation curtailment during low demand:** Voltage along the distribution feeder is controlled by constraining the injection of active power from DG. But it results in spilling of useful solar energy which is being highly discouraged by the PV panel owners.
b) **Reactive power control (VAR compensation) by reactive compensator:** To control the feeder voltage, reactive compensators absorb/inject reactive power at the connection point of DG.
c) **Area based OLTC coordinated voltage control:** Voltage is managed within the permissible limits by continuously changing the tap changer setting at the substation.
d) **Inverters at DG sites:** Inverter interfaced DGs (PV and wind) can be utilized to control the reactive power absorption/injection to regulate the voltage along the feeder.
e) **Consumption shifting and curtailing:** Shifting or curtailing the energy consumption by DGs can be another approach to regulate voltage.
f) **Energy storage:** By controlling the charging and discharging of the distributed energy storage system (ESS), the voltage fluctuation along the distribution network can be reduced.

Numerous alternative control solutions have been proposed in a number of literatures. Some common control structures were discussed in [72,73]. Some common control structures are,

i) Centralized control.
ii) Decentralized autonomous control.
iii) Decentralized coordinated control.

Now, these control structures are going to be discussed.

4.2.1. Centralized control

In this approach, the control decisions on different issues are solely taken by the central coordinator body. Status information from different network components is provided to the central coordinator via communication channels. Then the network management system analyzes the data and coordinator takes the control decisions and sends control effort signals to remote equipment.

To regulate the voltage along the distribution feeder and keep it within the permissible limit, the centralized controller requires having an accurate knowledge about the voltage at each network node. But, complete supervisory control and data acquisition (SCADA) system is hardly available in distribution networks. As for example: 11 kV distribution networks provide real time measurements only at primary substation. As a result, enough real time measurements throughout the feeders are seldom available. This shortages of real time measurements need to be compensated with estimated measurements. State estimation algorithms have been useful for long time designated for power transmission systems with lots of real time measurements [74]. But, transmission system state estimation algorithms cannot be directly used for the distribution network system for above reasons.

4.2.1.1. Distribution system state estimation. A significant amount of researches have been done on the transmission system state estimation (TSSE) and distribution system state estimation (DSSE) [74–84]. According to the researches, lack of real time measurements in the distribution network needs to be compensated with estimated pseudo-measurements. DSSE provides methodology to estimate the voltage at each node of the distribution network from available real time measurements and information. For the estimation, the estimator needs the following information,

1) Distribution network topology.
2) Impedance data.
3) Customer's load information.
4) Few real time measurements.

A functional block diagram for the estimator and controller is given below in Fig. 5.

Significant difference between the real time measured value and the estimated pseudo value can cause significant instability within the system. So, the critical points to measure the voltage should be carefully and strategically chosen. Strategically located measurements at key network nodes (such as at point of common coupling of DG or at a crucial network node where significant variation of voltage is expected) can supple the pseudo measurements. A series of load flow analysis might help to choose the critical points which will result in minimizing the variance on the unmeasured nodes.

We can minimize the error between the measurements and calculated values from the following equations [73].

$$\min J(x_1,\ x_2,\ \dots\dots\dots x_N) = \sum_{m=1}^{M} \frac{[z_m - f_m(x_1,\ x_2,\ \dots\dots\dots x_N)]^2}{{\sigma_m}^2} \tag{9}$$

$$x_{n+1} = x_n + G(x_n)H^T(x_n)W\big[z - f(x_n)\big]. \tag{10}$$

$$G(x_n) = [H^T(x_n)WH(x_n)]^{-1}$$

where,

x=State variables.

Z_m=Measurements.

$f_m(x_1, x_2,\dots\dots\dots x_N)$ = Measurement values calculated from state variables.

σ_m=Standard deviation.

H=Jacobean of the measurement set.

W=Diagonal matrix whose elements are the inverse of the measurement variance.

G=Variance of the estimated quantities.

The solution of (9) is the set of state variables that minimizes the difference between measurements and calculated values. The

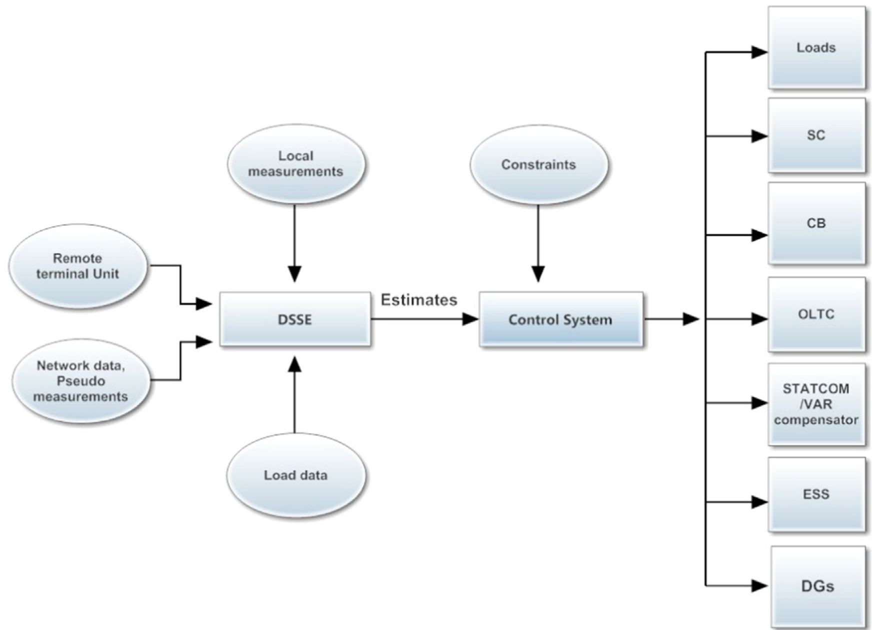

Fig. 5. A functional block diagram of distribution management system controller (DMSC).

minimization leads to iterative process where (10) is evaluated with the most recent values of state variables until convergence condition is met. With more integration of DGs, the network becomes more complex and interconnected. A distribution system state estimation (DSSE) algorithm that can be applicable for both radial and meshed networks is required.

4.2.1.2. Review of control methodologies. A centralized operation based active network management (ANM) has been discussed in [67]. In this article, three alternative approaches are evaluated to solve the voltage rise mitigation problem:

1) Generation curtailment during low demand.
2) Reactive power control by reactive compensator.
3) Area based OLTC coordinated voltage control.

The performance of different control strategies were relatively examined and evaluated. Revenue obtained from the coordinated OLTC control was found highest. But, the coordinated control scheme was not explained. For a higher penetration of DG, the annual generation curtailment was far lesser. Proposed control strategies likely increased the amount of integrated DGs.

Similar to transmission networks, centralized distribution system controllers have been discussed in [68,73]. State estimation method has been used to assess the voltage at each network locations and a wide area voltage control has been done by reactive power compensation and DG curtailment. OPF and cost benefit analysis (CBA) have been performed after that to evaluate the performance of voltage control. Capital costs, operation, maintenance and repair costs, AM schemes costs, savings from economies of scale, revenues from energy sales and environmental incentives were considered for cost benefit analysis (CBA). Distribution System State Estimation and active control of OLTC were performed in [85,86] to regulate the voltage Variation of voltages has been done at substation for controlling the voltage through the feeder. A control algorithm has been proposed to control (lower or rise) the automatic voltage control (AVC) target in such a way that the maximum and minimum node voltages along the feeder stay inside the permissible range. Similar to the control strategy of transmission system, coordinated voltage and reactive power control scheme has been followed in [87–89]. Alike [89], an objective function to minimize active power losses through distribution network has been considered in [90–94]. A multi-objective optimal voltage regulation algorithm is presented in [90]. In this paper, control devices (like Load ratio transformer, Static VAR compensator (SVC), Shunt capacitors and reactors) have been operated in a coordinated manner to minimize system losses and voltage deviation at each bus. With an active control over OLTC and reactive power support, voltage has been controlled in [91,92]. In [93], voltage regulation has been performed by controlling network parameters and power factor at which DG operates over several different periods in the day with different load levels. Ref. [95] focuses purely on reactive power control with an objective to minimize voltage deviation at each bus from specified reference voltage like [96] and does not utilize control equipment like OLTC tap settings, shunt capacitors similar to [69]. Voltage regulation was done in [96] by varying the settings of OLTC & load ratio control transformer and by utilizing shunt capacitors and SVC. A combined constant power factor control and variable reactive power control has been applied with an objective function to maximize the DG real power capacity in [69]. Comparison between centralized and decentralized control by some case studies has been done in [97]. In [98], control action has been done by utilizing OLTC and SVR. An objective function to maximize the magnitude of the lowest bus voltage has been considered in [99]. The aim was to keep the voltage at each bus within specified limits and the power supplied by each DG within its limits. Refs. [100,101] analyzed the effect of line drop compensation in distribution network Line drop compensation is imperfect when DGs are accommodated in the distribution network. This is because current measured at the OLTC terminals does not include the current supplied by the DGs. The proposed methodology in these articles mitigates voltage rise due to integration of DGs. However, the method does not utilize any voltage regulation equipment other than OLTCs. With minimum DG reactive support, an optimal volt/VAR control technique has been proposed for voltage regulation in [102]. But, minimizations of DG, active power injection curtailment and coordination of voltage regulation devices have not been considered. In [103], to reduce the optimization complexity, the distribution network has been divided into sub-networks but again coordination among OLTCs is not considered. An algorithm has been proposed in [104] to minimize system losses and tap operations in radial distribution network by coordinating OLTCs and static VAR compensators (SVC). In [105], decoupled active/reactive power control methodology through feedback linearization has been proposed for voltage regulation. But, this methodology has not coordinated voltage regulation devices. A one-day-ahead forecasting of load and renewable resources has been used to utilize the PV reactive power in [106]. The tap operations are minimized in this approach but active power injection curtailment is not considered during limited reactive power support. There can also be forecasting errors due to uncertain intermittent nature of renewable sources. The author of [107] proposed a methodology for voltage regulation by utilizing reactive power produced by PV-inverters. An algorithm operating in the continuous time domain has been adopted to solve a constrained dynamic optimization problem to minimize voltage deviation from reference value along the feeder. But, supplementary injection of reactive power increases inverter losses which reduces PV income. An optimal coordinated voltage regulation method in distribution network with vehicle-to-grid reactive power support (V2GQ) strategy has been proposed in [108]. A reactive market based on uniform price auction has been proposed by [109]. A control strategy of distributed energy storage system (ESS) utilizing OLTC, SVR and other traditional regulators has been proposed in [110] to reduce tap changer operation, to shave DN's peak load and to reduce power losses.

Centralized control methodology can provide the best performance possible, especially for small scale systems and for those networks where power flow is unidirectional. But, this methodology may become unpopular in future distribution networks for several reasons. They are as follows:

- These centralized control approaches require significant investments in communication assets and sensors. For high penetration of DGs into large interconnected and complex distribution networks, the implementation of centralized approach is not feasible.
- A large number of small scale DGs need to be controlled.
- Increased amount of uncertainties (due to intermittent renewable sources, faults, electric vehicles, storage units, dynamic loads, restoration, reconfiguration etc.).
- It causes large computational burden and numerical stability issues as it requires power flow solution at each time step.
- This methodology does not satisfy the effort to achieve '*plug and play*' property in which DGs can be connected to the distribution system with minimum revisions on feeder control and protection.

4.2.2. *Decentralized autonomous control*

In decentralised autonomous voltage control methodology, distribution network voltage regulation devices operate in response to the localised issues surrounding them. The controllers receive and analyse information from sensors surrounding them and perform necessary control effort on their respective locality [111].

4.2.2.1. Review of control methodologies. In [112], an intelligent decentralized hybrid voltage-power factor control (switching between the voltage control mode and power factor control mode) and a fuzzy logic based control strategy have been proposed and discussed to solve the voltage rise problem along the distribution feeder. As the distribution network is rapidly expanding and being complicated day by day, distribution network operators would require to incorporate more voltage control devices. But, the discussed hybrid voltage/power factor control can only be applied when no other voltage control device is near in the vicinity. On the other hand, to keep the power factor constant at the injection point, the generator settings need to vary with the load which needs constant monitoring of generation and load. In [113], a methodology has been suggested to utilize voltage source converters (VSC) with DGs to control the voltage by controlling the reactive power independent of the active power. Uniformly distributed generators and loads have been considered which is seldom practical. Most distributed energy resources (DGs) are preferred to operate at unity or constant power factor. Such as, PVs are required to operate at unity power factor to provide maximum power [114]. Sizes of DGs are considered small to put effect on the voltage regulation of the distribution feeder. On the other hand, in large interconnected systems, the Inverter based distributed generators with voltage control capability compete with one another to control the voltage and result in hunting among the generating units. Sometimes, they interfere with distribution network system operators' control (On load tap changing transformer operation) too and pose the possibility of undesired islanding [115]. For this reason, several countries do not allow voltage regulation by inverter interfaced distributed generators to prevent the risk of unwanted islanding.

A reactive power control approach has been made in [116] to turn large amount of DG connection into a non-perturbing power supply system along the distribution feeder. In this paper, instead of controlling the bus voltage, an approach has been made to ensure that generators active power injection alone does not occur significant voltage rise. Effectiveness and adequacy were analyzed and effect on DNO control was examined. Q^* control, Constant leading power factor and constant lagging power factor approaches were examined for voltage rise mitigation for two different cases (high load and no load). It was found that, Q^* control approach regulates the voltage rise problem for both the load situations and in between but with significantly increased tap changing efforts. It may allow to accommodate more DGs but in traditional fit and forget manner. Also, for a weak distribution network, if the DGs are operated in power factor control mode, it has an adverse effect on the generator terminal bus voltage. Ref. [100] suggested a decentralized line drop compensation method using OLTCs to mitigate voltage deviation. It also suggests that voltage control with DGs is possible when DG technology allow dispatching. Ref. [117] proposed an improved strategy from [112] to control the voltage. It suggested utilizing generation curtailment strategy when hybrid voltage-power factor control is not effective. It prevented excessive voltage rise in a cost effective manner. Ref. [118] proposed a method that optimized the existing network infrastructure. Tap settings of the OLTC were reduced in such a way that can accommodate the raised voltage within the permissible limit. But, traditional OLTCs are not fast enough during the situations of sudden dynamics as they require some physical adjustments to make. Also, the amount of tap changes should be kept within limited value. The DG operating power factor was varied to reduce the distribution network dependency on transmission network for reactive power supply at any given period in [119,120] examined different operation modes (constant voltage, constant current and constant power factor) of DG and found that the losses are higher when DGs are operated at constant power factor mode. Ref. [121] suggested a decentralized control method where the network was divided into groups of adjacent buses. DGs monitor voltage within their respective groups and vary the reactive power utilizing inverters to adjust their terminal voltages.

Currently, inverter interfaced DGs are not permitted to control voltage locally according to 1547 IEEE Standard [122]. But IEEE P1547.8 has developed practice for establishing methods for expanded use of 1547 [123]. Researchers are working on the situations when local voltage control by inverter interfaced DGs should be allowed. Moreover, inverter interfaced DGs can deliver fast reactive power support. As a continuation, [124–133] have showed that the reactive power capability of inverter interfaced distributed generators can improve distribution network systems operation. They mainly focused on the volt/VAR control strategy of inverter interfaced DGs. The voltage control objective is accomplished with a piecewise linear droop characteristic in [126–130], which determines the reactive power injection as a function of the voltage magnitude at the PV inverter terminals. Refs. [134–138] showed how distributed control of reactive power (part of volt/VAR control strategy) can serve to regulate voltage and minimize resistive losses in a distribution circuit. Refs. [139,140] suggested that the integration of MPPT (maximum power point tracker) with real and reactive power control capability can improve the overall efficiency of the system. Refs. [141–146] suggested local linear controllers to improve voltage quality but they need high bandwidth communication with distribution network system controllers. [147] suggested a local linear controller that substitutes reactive power for real power for mitigating voltage deviations. This controller does not require high bandwidth communication like [141–146] but its performance was not assessed in larger interconnected distribution systems with multiple DGs. Ref. [148] showed that DGs have the ability to provide flexibilities on curtailing or shifting their energy consumption for mitigating voltage fluctuations.

Being autonomous is one of the main advantages of decentralized local control. Controllers receive information of their local network status, analyze it, select an appropriate control effort and then implement that effort. As a result, decentralized autonomous controllers have the capability and flexibility to respond to load fluctuations. There are some drawbacks too. They are as follows:

- Voltage control devices undergo high stress.
- Local voltage controllers compete with one another and interfere one another's operations.
- Power losses through distribution feeder get increased.
- DGs energy capture is not maximized.

4.2.3. Decentralized coordinated control

In this control methodology, DGs communicate with one another to recognize the local states of whole distribution system. They exchange information of their individual states, control actions, plans and requests to coordinate with one another for achieving a global approach to mitigate the voltage rise issue in an efficient way.

Voltage control devices should coordinate with one another for proper voltage regulation. With proper coordination, voltage deviation issue can be tackled efficiently. As a result, peer-to-peer, multiagent, coordinated control methodology has been motivated by operators. Multi-agent system (MAS) has been introduced recently as a potential technology for voltage regulation applications. Some basic definitions of MAS concept and its application in power system have been discussed in [149]. They are briefly described below:

4.2.3.1. Agent. An agent is a software (or hardware) entity that is located in some environment and capable of reacting autonomously to changes in that environment. It monitors its environment either physically through sensors or collecting data from other resources.

4.2.3.2. Intelligent agent. Intelligent agents show some intelligent features and flexible autonomy while taking decisions for reactions to the changes in the environment.

- Intelligent agents can react to changes in a timely fashion based on the changes in the environment.
- Intelligent agents can set their own goals and can alter over time.
- Intelligent agents can interact with other intelligent agents. They not only exchange data but also negotiate and solve complex interactive problems.

4.2.3.3. Multi-agent system. Combination of more than one *intelligent agent* and *agent* within a cooperative system is called multi-agent system (MAS). MAS is capable of dynamic re-organization of its overall function. This decision is taken by intelligent agents based on the signals, information and data from the environment on an ongoing basis. A functional diagram of the active network with MAS control in radial distribution network is given below in Fig. 6.

4.2.3.4. Review of control methodologies. An active network needs to be constructed with the support of MAS. The radial distribution

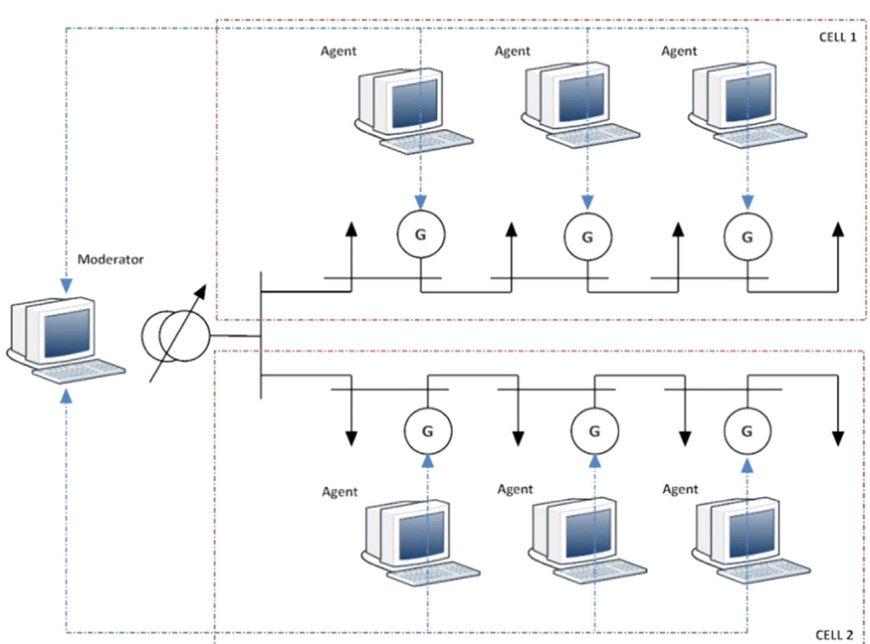

Fig. 6. An active network with MAS control in radial distribution network divided into subnetworks (cells).

network is divided into several sub networks (feeders). For each feeder a local control area (cell) needs to be established. Within the local control area (Cell), each controllable component (such as, controllable generators, loads etc.) will have an agent that can operate autonomously with local goals or cooperate with other agents to achieve global goals. Intelligent agents can communicate with one another in two approaches [150].

1) Phone-based communication.
2) Internet-based communication.

A multi-agent optimal reactive power dispatching strategy was suggested in [150] for voltage rise mitigation in a single feeder. This study can be advanced by considering voltage regulators and shunt capacitors in operation and providing a proper simulation model. Refs. [151–156] suggested multi-agent frame works for proper voltage control in distribution network. But, a well-defined control structure and operation mechanism could be presented. This study can be upgraded by developing proper communication and coordination protocols among voltage controllers. Ref. [157] considered these issues that were not well discussed in [151–156]. A methodology has been proposed to achieve decentralized coordination among distributed systems in [158,159] via multi-agent consensus theory. A secondary voltage control strategy has been discussed in [160] using multi-agent system theory but it focused on transmission systems. Refs. [161–163] suggested a strategy where each network node can request for reactive power support in the situations of voltage deviation throughout the feeder. Ref. [164] suggested a methodology where each node of the distribution network observes the deviation of its local voltage from the nominal value and voltage deviation state is initialized. Then, all the nodes share information and inverters coordinate to control the voltage jointly.

To implement multi-agent system, several things need to be considered. They are: data standardization, intelligent agents design, platforms and communication languages. Foundation for Intelligent Physical Agents (FIPA) is the body that develops agent's standards and sets agent communication languages. Java Agent Development Framework (JADE) is a popular platform for multi-agent system in power engineering applications. As JADE acts as a middleware for developing distributed applications, its scalability needs to be evaluated. Three important variables need to be considered while evaluating scalability of JADE. They are (1) the number of agents in a platform, (2) the number of messages for a single agent and (3) the number of simultaneous conversations a single agent gets involved in [165]. JADE tries to support as large system as possible, but in case of large-scale implementation, the processing load tends to increase [166] as agents are usually programmed with interpreted language and need to keep rigorous interoperability standards in check which may cause data processing overheads.

5. Conclusion

Voltage regulation challenge along the distribution feeder has attracted the rapidly growing attention of industries and researchers and this issue will be more significant in near future due to increased integration of renewable DGs in the lower/medium voltage network. In this paper, we presented how the operation, protection and stability of the distribution network gets impact due to increased accommodation of renewable DGs. Traditional control devices are not fast enough to regulate the voltage when large amount of intermittent renewable DGs are connected. Development of advanced control strategy is the fundamental key to penetrate large amount of intermittent renewable DGs without putting significant adverse impact on distribution network operation and stability. Lots of researches are going on to establish better control over the feeder voltage when large amount of renewable DGs are accommodated. Utilization of energy storage devices is also a promising strategy to mitigate these issues and to ensure a sustainable power supply. Energy storage devices can support the grid during high peak demand and they can be utilized to shift consumer loads from peak time to off-peak time [167].

Qualitative analysis was performed in this paper for all kinds of voltage control approaches. Researchers have used several control devices like OLTCS, SVRs, SCs, STATCOM/FACTs devices, PWM inverters, energy storage devices etc. and have utilized several control methodologies. This article also summarized recent developments in control approaches like centralized control approach, decentralized autonomous control approach and decentralized coordinated control approach. These control approaches have their own advantages and disadvantages which have been discussed in previous sections. Centralized control approach is very popular for small networks where power flow is unidirectional. As power system is expanding day by day and power flow is being bi-directional nowadays due to increased accommodation of DGs, this approach is losing its popularity. On the other hand, decentralized autonomous control approach shows the flexibility to respond to load fluctuations due to its autonomous characteristics. But, it has got some disadvantages too like high stress, operational interference, increased power loss etc. Decentralized coordinated control approach is gaining interest of researchers nowadays because of its coordination capability among control devices which helps to achieve a global goal. In addition, as we have reviewed, voltage regulation of the modern distribution network is a challenging research area and still under development. Researches are going on and significant efforts are still necessary to mitigate this issue.

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