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Review article

State-of-the-art technologies for volt-var control to support the penetration of renewable energy into the smart distribution grids

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ABSTRACT

The currently deployed volt-var infrastructure for voltage optimization in distribution networks would be unable to meet the stringent technological requirements of the electric power grid of the 21st century. If not handled correctly, conventional voltage control systems could inhibit the ubiquitous deployment of renewable energy resources into the future smart grid. For example, the incorporation of renewable energy sources and the new types of energy storage systems in the distribution system provides a threat for the seamless voltage control. In order to overcome such barriers, smart volt-var control methods are needed to be studied and implemented. However, achieving such goals requires a complete background of the contemporary strategies and developments of the volt-var technologies. So far, various techniques have been developed to accommodate the large penetration of renewable energy sources into the distribution networks. This paper provides a comprehensive review on the current technologies that enable distribution system operators to select appropriate strategies for the volt-var control in renewable-rich power grids. This review article investigates the emerging volt-var technologies for the distribution network along with their advantages and disadvantages. It also outlines some of the open research problems and future directions in this topic.

Contents

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Abbreviation

RES	Renewable energy resources
MINLP	Mixed integer non-linear programming
ESSs	Energy storage systems
CBs	Capacitor Banks
OLTC	On-line tap changer transformers
PV	Photovoltaic
VR	Voltage Regulators
PET	Power electronic transformer
NSGAII	Non-dominated sorting genetic algorithm
DSO	Distribution system operator
TSO	Transmission system operator
MIQP	Mixed Integer Quadratic Programming
EVs	Electric vehicle
DGs	Distributed generations
ABC	Artificial bee colony algorithm
OPF	optimal power flow
LVDI	Load-weighted voltage deviation index
CVR	Conservation voltage reduction
DRP	Demand response programs
TOU	time of use
CPP	Critical peak pricing
PTR	Peak time rebate
LV	Low voltage
MV	Medium voltage
ZIP	Load model (Z=constant impedance, I=constant current and P=constant power)
SOP	Soft open point
TLs	Thermostatic loads
VO	Voltage optimization
Discos	Distribution system companies
THD	Total harmonic distortion
DLC	Direct load control
ASM	Ancillary service market
I/C	Interruptible/curtailable service
CAP	Capacity market program
EDRP	Emergency demand response program
DB	Demand bidding/buyback
TOU	Time of use
CPP	Critical-peak pricing
RTP	Real-time pricing
VVC	Volt/Var Control
MAS	Multi Agent System

1. Introduction

In the present era, the energy demand is rising significantly due to the increased number of industries, homes, and commercial loads. However, supplying this growing energy demand by increasing the generation from traditional fuel-based sources such as diesel generators has the worst effect on the environment (Silva et al., 2020). For instance, the global electricity generation from renewable energy sources is expected to grow 2.7 times between 2010 and 2035 (Ellabban et al., 2014). Some quantitative information related to RES usage in different parts is shown in Fig. 1. As can be seen from this figure, it is clear that in 2010, 2 percent of renewable energies were used for transportation systems, while it was doubled in 2010 and it is interestingly going to be tripled in 2035. In terms of heat demand supplied by RESs, we may experience less increase compared to other categories. The reason may be the variety of sources of supplying heat demand like gas, gasoil, etc. Surprisingly, electricity generation will accommodate higher amount of RESs to generate power. To facilitate the integration of higher levels of variable renewable generation into the grid, several countries have passed legislations to create an enabling environment for renewable energy development and ensure system reliability (Ellabban et al., 2014).

Although RESs have extraordinary advantages, such as cleaner environment and zero carbon emission, they impose various technical issues for distribution system operators, especially in terms of power quality and reliability (Lehtola and Zahedi, 2020). This is due to the uncertainty in their generation, which can result in power grid issues such as over-voltages and under-voltages. These latter may damage network equipment and break consumer devices that are not able to tolerate surplus voltages, such as motherboards and network adaptors.

The process of voltage control in distribution networks, namely the volt-var control, plays a major role in smart distribution grids. Fig. 2 highlights the different volt-var control technologies in distribution networks. Since various industries are taking steps towards automating different parts of the systems, ensuring proper coordination among the different equipments is essential. For example, a utility may want to increase the level of voltage by an OLTC. However, it is essential to check its effects on consumers. To perform voltage control in the distribution network, various technologies, e.g., online-tap changer transformer, capacitor banks, and techniques such as load modeling, demand response programming have been proposed in the literature. For instance, the authors of Jabr (2019) and Pamshetti and Singh (2019) noted that voltage violations in the active networks can be mitigated by properly coordinating smart PV inverters. Petinrin and Shaabanb (2016) focused on solutions involving the joint use of voltage control and mobile energy storage systems (Jeon and Choi, 2022). Voltage control methods considering on-load tap changer transformers for networks with renewable energy sources are illustrated in Sarimuthu et al. (2016). Energy storage systems were also utilized in Mak and Choi (2020) and Prabpal et al. (2021) as a novel technology to deal with volt-var management in distribution grids. An OLTC-inverter coordinated voltage regulation method for distribution network with high penetration of PV generations was proposed in Liu et al. (2019).

Research works addressing volt-var controls in distribution networks are scares in the literature. To begin with, a review on voltage management via distributed energy resources including generation units, energy storage, and electric vehicles can be found in Murray et al. (2021). The review iterated that properly coordinating the distributed generation resources constitutes a great solution to mitigating the voltage violations in active networks. Voltage regulation in photovoltaic-rich distribution networks was investigated in Chaudhary and Rizwan (2018). From the results, it was found that energy storage systems and smart inverters can be an efficient measures to cope with the voltage rise issues associated with PV generation.

To the best of the authors knowledge, none of the existent literature has provided a comprehensive up to date review on

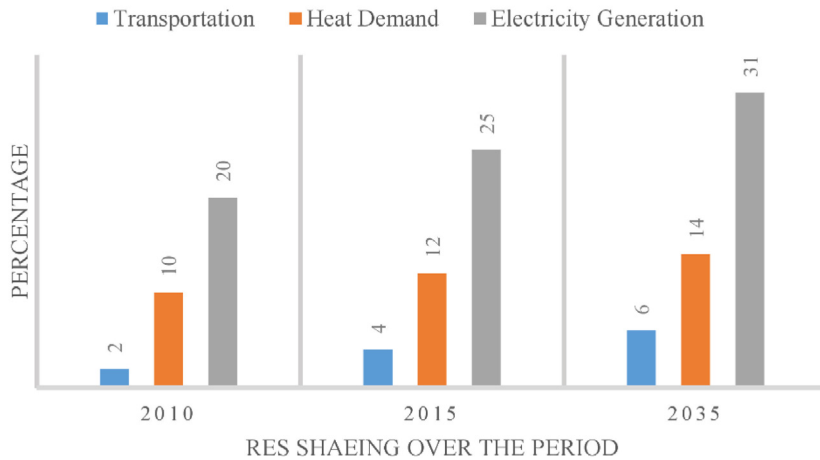


Fig. 1. Share of RES per category (Ellabban et al., 2014).

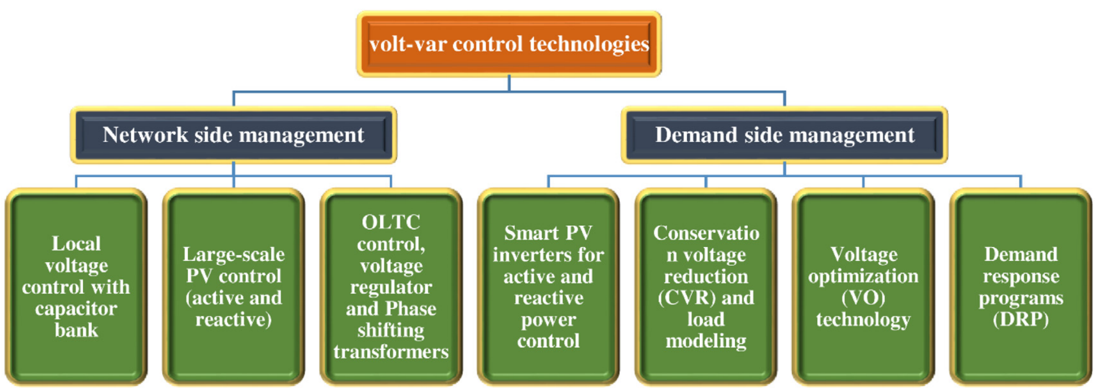


Fig. 2. Classification of volt-var control technologies.

all voltage control techniques in the distribution network. For instance, demand response program is a key factor in volt-var management schemes. However, such technology has been overlooked by researchers who are active in this field. The aim of this paper is to provide a comprehensive review on available voltage control methods and devices for voltage management in the distribution network. Since there exist numerous ways to control the voltage and reactive power in distribution networks, being acquainted with these technologies and the most recent research in the field is critical for practitioners and researchers alike.

The remainder of the paper is organized as follows. Existing volt-var schemes on distribution networks are discussed in Section 2. A summary about these techniques along with a comparison analysis is outlined in Section 3. Some research gaps associated with the volt-var optimization are finally discussed in Section 4.

2. Network side management

One of the most important responsibilities of distribution network operators is to ensure the reliable delivery of electric power to the consumers. Keeping voltage within the acceptable range is important in distribution levels. To this end, various techniques could be taken into account which are separately discussed as follows. A classification of existing vol-var technologies is illustrated in Fig. 2.

As can be seen from Fig. 2, volt-var technologies are divided into two main categories: network side management and demand side management. For the network side, operators try to effectively control the capacitor banks, large-scale PV inverters, online tap changer transformers, voltage regulators, and phase shifting transformers. For the demand side, consumers (residential, industrial, commercial) are actively participated in voltage and reactive power management via the roof-top PV inverters, energy conservation, voltage optimization technology and demand response programs.

In what follows, we proved a detailed description of each approach.

2.1. Local voltage control with capacitor bank

Capacitor banks are one of the most common technologies used for reactive power compensation and voltage control in distribution networks. Fig. 3 illustrates a capacitor bank switching in the power distribution grid.

As clearly seen from this figure, a set of shunt capacitors are installed into a bus and switched according to different objective functions, such as the power factor, loss minimization and so on. A significant number of power demand, such as the one by motors for instance, is for reactive power. Such demands, not only decrease the energy transfer between lines, but also increase the power losses. In order to compensate for such issues, reactive power compensators such as capacitor banks are utilized in distribution grids as cost-efficient solution.

Ameli et al. (2017) proposed a method for improving the performance of distribution networks based on network reconfiguration and capacitor switching. The problem was formulated to minimize the cost of power purchase from the substation,

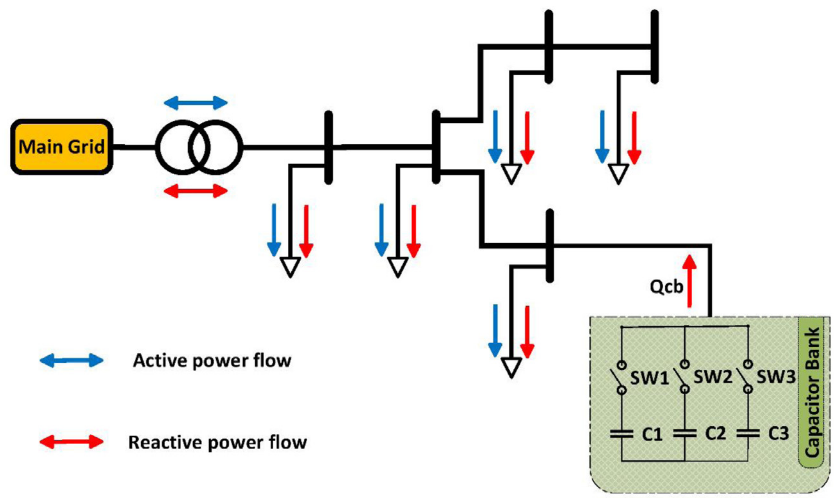


Fig. 3. Capacitor bank in a distribution network for reactive power compensation.

cost of customer interruption penalties, transformer loss, and the switching costs (capacitor bankswitching). The problem was solved using an evolutionary algorithm. By interacting with the utilization of energy storage systems, in Islam et al. (2021), a planning approach is devised for the simultaneous allocation of energy storage systems (ESSs) and Capacitor Banks (CBs) with the aim of decreasing the voltage drop. In more detail, the optimal location and sizing of ESSs and CBs are calculated. Then, under different case studies, it was shown that combining ESSs and CBs could be a reliable solution to cope with the system vulnerability to voltage drops. Similarly, a multi-objective scheme based on salp optimization algorithm was developed in Shaheen and El-Sehiemy (2021) for technically and economically improving the performance of distribution systems via CBs allocation. With regard to the economic aspect, minimizing the power loss and investment of CBs were taken into account. The voltage deviation was used as the second objective function to model the technical operation of the system. Implementation of the proposed method to a real case in Egypt showed a significant reduction in the economic objective function. In Singh et al. (2020), the moth search optimization was modified to allocate the distributed generation and capacitor banks in the presence of on-line tap changer (OLTC) transformers so as to minimize power losses and voltage deviations. The approach was implemented on the IEEE 33 and IEEE 118 bus benchmarks. After comparing with other published works, it could be seen that this method is superior in terms of planning such devices in the distribution networks. This is because the algorithm could find better solutions (less objective function). In Navesi et al. (2022), the switchable CBs were allocated in the distribution network considering the network reconfiguration under high penetration of renewable energies. The problem was formulated for power loss minimization and voltage deviation reduction. The PSO algorithm was used for solving the optimization problem. The obtained results showed that the coordination of CBs in the reconfigurable grids leads to the secure operation of the system. Simultaneous allocation of DGs and CBs were also investigated in Gholami and Parvaneh (2019) for power loss minimization and voltage enhancement. The approach was implemented on two IEEE test networks using a modified salp swarm optimization algorithm.

Based on the above discussion, we can state that CB is a great way for controlling the voltage in distribution systems since it is a cost-efficient device that can easily be coordinated with other devices such as OLTC. However, it has several drawbacks compared with smart PV inverters. For instance, CB is not as flexible as smart PV inverters and may bring power quality issues due to switching and grid resonance. PV inverters are bi-directional devices, hence they can absorb and inject reactive power while CBs just absorb the reactive power. This in turn results in the inefficiency of CBs in controlling the over-voltage in the system. As explained in the aforementioned literature, considering a co-ordinated control that includes CBs and other devices provides better voltage control than just controlling the CBs.

2.2. Large-scale PV control (active and reactive)

Grid integration of solar photovoltaic (PV) power has recently shifted from rooftop installations to large utility-scale solar PV power plants, which can be attributed to a number of factors, including the falling prices of solar PV technology, as well as regulatory and policy measures for large-scale renewable energy integration.

To determine the realistic reactive power support capability of a solar PV plant, a methodology for accurate calculation of solar PV inverter reactive power capability was investigated in Karbouj et al. (2021). To this end, under extreme weather conditions, the precise reactive power capability of solar PV inverters was calculated for two locations in Saudi Arabia and India. Then, a self-adaptive voltage control was proposed to enable the participation of large-scale PVs in the voltage control ancillary service based on the precise estimation of reactive power capability. Fig. 4 depicts the process of solar PV inverter reactive power capability under weather conditions. The main shortcoming of this paper is the fact that it did not consider the DC voltage of the inverter while optimizing the reactive power, which has a great impact on the inverter's output current. The higher the DC link voltage of the inverter, the lower its active and reactive capability. The DC link voltage can be changed based on weather conditions and the active power set points.

Step Voltage Regulators (SVRs) have always been a reliable device for voltage regulation in long distribution feeders (Wang et al., 2018). Large-scale PV plants are also implemented as an ancillary service to compensate for the reactive power which leads to voltage control in distribution grids. Although SVR and PV are great measures for voltage regulation, the tap operation of SVRs and PV fluctuations are their shortcomings. Authors in Wang et al. (2018) proposed a coordinated scheme for managing SVRs and the reactive power of PVs. Its implementation to a real case study at Queensland University, Australia showed that the proposed approach resulted in minimizing the number of SRV tap operations and limiting reactive power capacity, while maintaining the

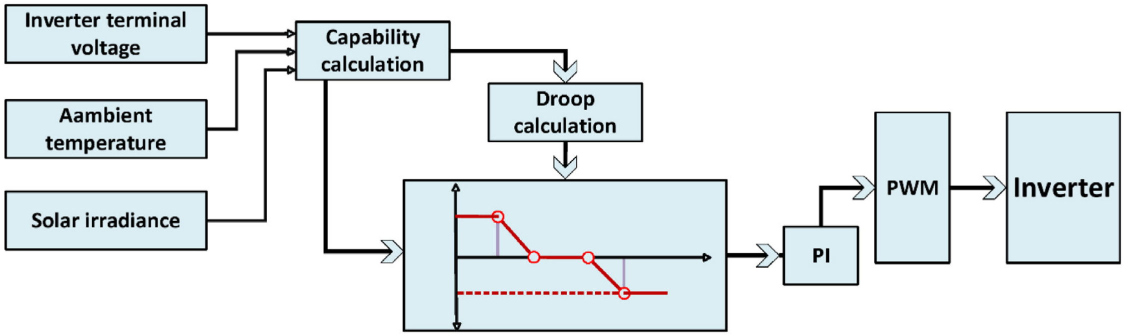


Fig. 4. Accurate calculation of solar PV inverter reactive power capability under weather conditions.

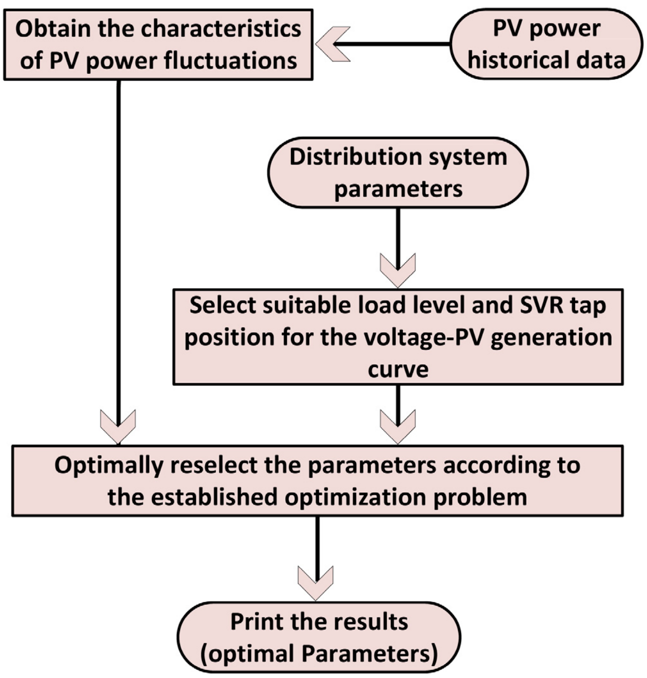


Fig. 5. The process of managing step voltage regulators and the PVs' reactive power.

network voltage within acceptable ranges. Fig. 5 illustrates the optimization procedure for the step voltage regulator and reactive power of PV inverters.

It is clear from this figure that an optimization is executed to find the optimal position of the voltage regulator and the amount of reactive power which is necessary to maintain the voltage within the acceptable ranges.

In Resch et al. (2021), a techno-economic solution, that integrates PVs and batteries into the network, was proposed and implemented to a practical network in Germany as an alternative method to traditional expansion planning approaches. Hybrid AC/DC distribution grids were also used to accommodate large-scale PV generation units (Gao et al., 2019). The economic dispatch of the mixed AC/DC system was formulated in the presence of power electronic transformers (PET), for the flexible control of AC and DC power flows, while maintaining the security constraints of the system such as bus voltage, branch current carrying capacity, and the efficient operation of the power electronic converters. The investment cost and power loss minimization were considered as bi-objectives and solved via non-dominated sorting genetic algorithm (NSGAII). Compared with published works that merely consider AC grids, combining PET, hybrid AC/DC grids, and PVs leads to less operational cost as well as less PV curtailments.

An investigation was provided in Valverde et al. (2019) to control solar PVs in distribution networks with the aim of supporting the reactive power of transmission networks. To this end, some commands were shared between the distribution system operator (DSO) and transmission system operator (TSO) to control the distributed generations under Volt/Var control schemes. The approach was implemented on a real network in Switzerland to assess this interaction on networks' voltage support. Fig. 6 depicts the control scheme for PVs' inverters to support upstream networks.

Ruan et al. (2020) proposed a voltage control strategy based on the network partitioning of distribution networks. The scheme led to decreasing the computational burden, since the network was partitioned into several parts. A distributed algorithm based on Lagrangian dual relaxation was utilized to solve the model which converges in a finite number of iterations, thus resulting in less complexity. Fig. 7 outlines the voltage control strategy based on the network partitioning model. In other words, the network is separated into several regions and the volt-var schemes are applied to each partition. This, not only leads to reducing the system complexity, but also helps making quicker decisions in emergency situations, such as severe grid faults, contingencies and power outages.

In Chamana and Chowdhury (2018), a new zone-based multistep scheduling scheme was proposed for on-load tap changing (OLTC) transformers, capacitor banks (CBs) and step voltage regulators (SVRs), considering large-scale photovoltaic (PV) sources. The regulators were managed in distribution grids to minimize the PV curtailment and voltage deviation. A Mixed Integer Quadratic Programming (MIQP) solver was utilized to solve the sub-objective optimization problem at each stage. Comparison of this method to conventional volt/var controls confirmed its superiority in terms of reduced use of regulators and PV inverters' minimal power output. Although the linear formulation has several advantages, such as faster response, reaching global optima, etc., it raises the optimality gap which makes it not applicable to cases where exact results are vital. To this end, authors in Chang and Chinh (2020) provided a planning approach for the optimal integration of PVs in distribution systems using the Coyote Optimization Algorithm. Implementation of the proposed approach to two practical networks and comparison analysis with other evolutionary algorithms showed that this method outperformed other existing methods in terms of finding appropriate solutions with faster convergence rate.

2.3. On-line tap changer (OLTC) control, voltage regulator (VR) and phase shifting transformers

On-line tap changers (OLTC) and voltage regulators (VR) are used to change the level of voltage in distribution networks. Both of them have the same functionality. However, OLTCs are

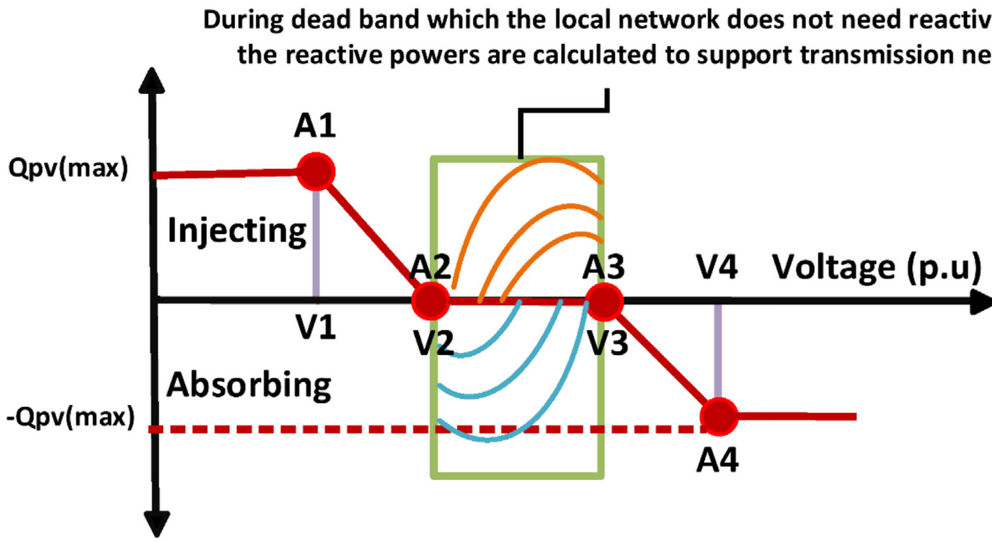


Fig. 6. The controlling scheme for PVs' inverters to support upstream network.

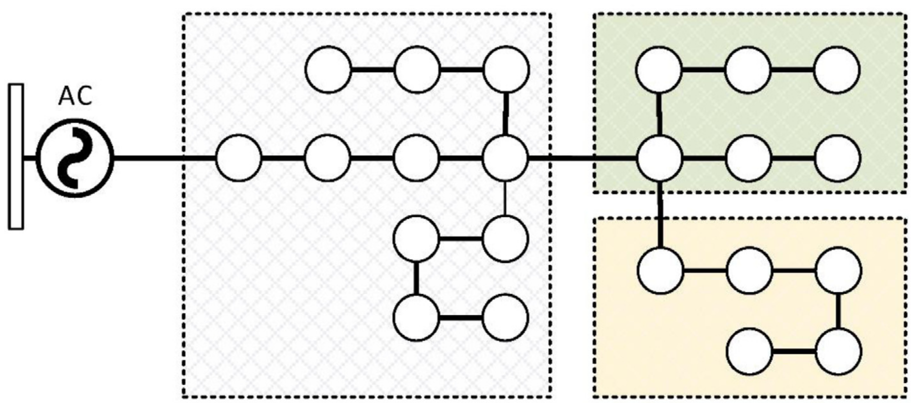


Fig. 7. A network is partitioned into some sub-networks.

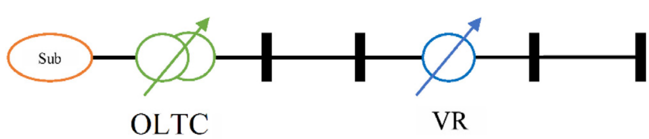


Fig. 8. Integration of on-line tap changer and voltage regulator in the network.

installed after the substation and have an impact on the entire voltage of the network, whereas VR are used to regulate the voltage of a specific section of the network. Fig. 8 illustrates the integration of OLTC and VR in the network. VRs are commonly installed in the long radial distribution network to maintain the far-end voltage profile.

OLTC transformers are one of the known devices frequently used in the voltage management of distribution feeders. PVs are also inevitable parts of the distribution grids of the 21st century. Due to the fluctuation of PVs' output, energy storage units are also used. Hence, coordination schemes for OLTC in the presence of ESSs and PVS are essential for ensuring acceptable voltage magnitudes across the distribution network. Accordingly, an optimization problem is formulated in Tewari et al. (2021) to minimize the voltage deviation, while reducing the number of tap position operations and extending ESSs' lifespan. A reported comparison analysis found the proposed coordinated approach to be superior to traditional uncoordinated schemes in terms of voltage regulation and resource utilization in distribution systems. Nonetheless, uncertainties have direct effects on power system operations and voltage management is no exception. Thereby, authors in Ali et al. (2021) proposed a probabilistic model aiming at maximizing the hosting capacity of PVs in distribution grids. This model is based on controlling different devices in distribution grids, including OLTC, reactive power of PV inverters, and electric vehicles (EVs). The optimization problem was formulated and solved under a bi-level condition. The lower level schedules the charging/discharging power of EVs, OLTC taps to support the reactive power, while the upper level maximizes the sizing of the PVs. This investigation showed the efficiency of this model to optimally schedule the mentioned devices with a higher hosting capacity of PVs. In order to enhance the stable and secure operation of distribution systems, the stability of the network should be satisfied under volt-var schemes. Accordingly, a multi-timescale voltage stability-constrained volt/VAR control scheme was proposed in Zafar et al. (2020). The approach coordinated OLTCs as slow-timescale corrective actions while considering PV inverters and ESSs as fast-timescale corrective actions. The approach provides various techno-economic advantages, such as power loss minimization, reliable operation of the system, eco-friendly approach due to higher integration of renewable energies, and taking the advantages of power solvers into account. Due to the real-time implementations and the fact that the operational schemes are executed one day-ahead, the management

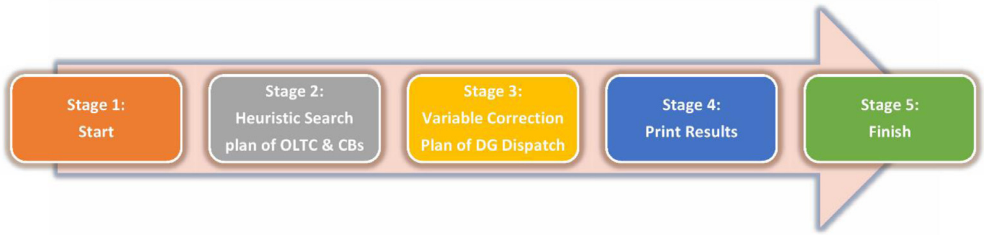


Fig. 9. The process of reactive power dispatches into the system.

of equipment such as OLTC, CBs, etc., must be coordinated under different situations with the proper time complexity. Accordingly, the problems are separated into different stages which not only decrease the computational burden, but also provide precise results. For example, in Chen et al. (2019), a new two-step strategy was proposed for the dynamic reactive power dispatch in distribution grids, considering distributed generations (DGs). In the first step, an optimization approach using the niche genetic algorithm is implemented to coordinate several devices comprising OLTC, capacitor banks (CBs) and DGs. Following this step, a day-ahead plan for OLTC and CBs is made based on an artificial bee colony (ABC) algorithm and sequential fuzzy c-means. In the last step, the dispatch plans of the devices, including OLTC and CBs are applied to recalibrate the day-ahead dispatch of DGs. The approach was implemented on several case studies to verify its efficiency. Fig. 9 illustrates the various stages of the reactive power dispatch in the system.

The distribution systems in some regions such as South Africa have long lines with low capacity (Tshivhase et al., 2021). Such systems experience various voltage fluctuations when combined with DGs. Since these networks suffer when hosting DGs, devising appropriate coordinated strategies is vital to maintaining voltages within acceptable boundaries. In Tshivhase et al. (2021) a simultaneous coordination of OLTC, voltage regulators(VRs), DGs and ESSs was proposed for the voltage control in distribution feeders. Its implementation to a real-case study in Africa confirmed its ability to manage the voltage in distribution grids with long lines. Uncertainties stemming from load variations and renewable energy resources fluctuations has a direct influence on the operational and planning schemes in power systems. Accordingly, assessing the impact of uncertainties on volt-var optimization is also highlighted to have a robust decision under such circumstances. Consequently, a robust approach was proposed in Azarnia and Rahimiyan (2022) to handle the uncertainties stemming from load variations and renewable resources in volt-var control optimization. Compared with other methods, which used stochastic strategies, the approach in Azarnia and Rahimiyan (2022) was shown to require less computational burden and provide more accurate results. Authors in Bagheri et al. (2018) proposed a coordinated model for voltage regulators (VRs) with the aim of mitigating the overvoltage in distribution networks. This was implemented on a 123-bus network considering different scenarios. The obtained results showed that this can be a great method in decreasing voltage fluctuations. In Li et al. (2018), a scheduling scheme for OLTC was provided to harvest higher solar energies in distribution grids. It was formulated with the aim of minimizing the number of OLTC switching and voltage deviation. A convex model was considered to lower the computational burden so that a 1623-bus/40OLTC network would have taken merely 1.1 s. It was compared with other methods and the obtained results showed that the integration of OLTC into the system brought about higher PV accommodation (67% more PVs) without violating any technical constraints. In the aforementioned papers, there are some devices in coordination schemes. However, A voltage management strategy was similarly proposed in Olatunde et al. (2020) for distribution networks integrated with OLTC, (CBs) and energy storage systems (ESSs). From the results, it can be observed that simultaneous coordination of devices decreases more power loss and improvement of voltage profile while higher renewable energies are penetrated into the system.

Phase shifting transformers are used for changing the angle of voltage in order to achieve different goals. In Ding et al. (2017), the conventional optimal power flow (OPF) problem was embedded with phase shifting transformers. The results showed that using phase shifting transformers bring both technical and economic benefits when integrated with the OPF problem. For instance, a better economy is achieved after getting phase shifting transformers involved. Regarding the technical side, phase shifting transformers can assist in producing a feasible solution compared to a previously unsolvable OPF problem. Similarly, the authors in Ashpazi et al. (2015) investigated the optimal sizing and sitting of phase shifting transformers to increase the transient stability of power grids. Implementation of the proposed approach to two case studies showed that optimum allocation of phase shifting transformers is an efficient alternative to improving system stability. Due to the advantages of DC grids, they are operated in the presence of AC grids, thus resulting in AC/DC grids. Accordingly, such networks have a wide range of voltage control devices with various control characteristics. In Qiao and Ma (2020), a voltage management scheme was proposed for controlling the different devices. More specifically, OLTC and CBs were scheduled every 2 h, thus resulting in extending their lifespan. However, generation resources were scheduled every 30 min because of their fast response. Case studies were implemented on an IEEE benchmark and showed substantial loss reduction and voltage improvement compared to traditional methods. Fig. 10 depicts the line diagram of a network integrated with an on-line tap changer, capacitor bank, and microgrid. Note that an OLTC is installed after the substation which has a direct effect on the voltage of the entire network. Capacitor banks are also local compensators often used to mitigate the effects of reactive power on the network. Interestingly, microgrids with different distributed energy resources, such as renewables, energy storages, etc. are also integrated to control the voltage of the system.

The research in Kim et al. (2017), provided an optimal reactive power support for distribution networks by means of synchronous distributed generators (DGs). In other words, the reactive power dispatch of DGs along with switching OLTC and capacitor banks (CBs) are scheduled were an hourly basis according to the forecasted load demand. This is formulated for power loss minimization as well as decreasing the number of switching of OLTC and CBs throughout the period. This nonlinear day-ahead approach was solved using a PSO algorithm. The reported simulation results showed that when DGs are utilized as an ancillary service to support the reactive power in the presence of scheduling OLTC and CBs, the system's performance increases significantly. PV fluctuations, however, lead to voltage violations. To this end, the research reported in Ma et al. (2021) proposed

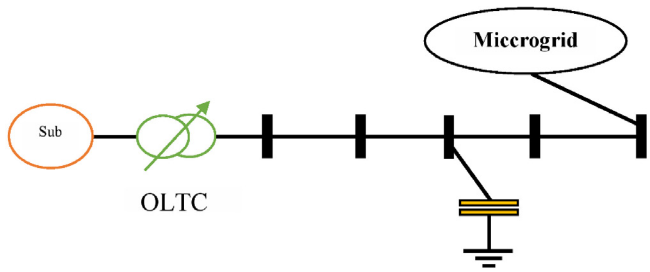


Fig. 10. Line diagram of a network integrated with on-line tap changer, capacitor bank, and microgrid.

a centralized approach to maintain the voltage of distribution systems within acceptable boundaries by coordinating OLTC, CBs, and PVs. The optimization approach was formulated based on the non-dominated sorting genetic algorithm (NSGA-II) with the aim of minimizing power losses. The obtained results confirmed the appropriateness of this method for such operation of the distribution system.

OLTC and VR are efficient solutions for voltage management in distribution networks with high levels of renewable energy generations. One of their major benefits is the fact that they do not cause significant extra power loss compared to other Q-based alternatives. However, they are not as quick as other inverter-based sources such as PVs and ESSs.

3. Demand side management

In the past, when demand was solely supplied by power plants, power systems were unidirectional. However, in recent years, an ever growing number of customers have installed renewable energy sources such as PV arrays to supply their demand. Accordingly, properly managing such resources is essential to ensuring the secure operation of the entire power system.

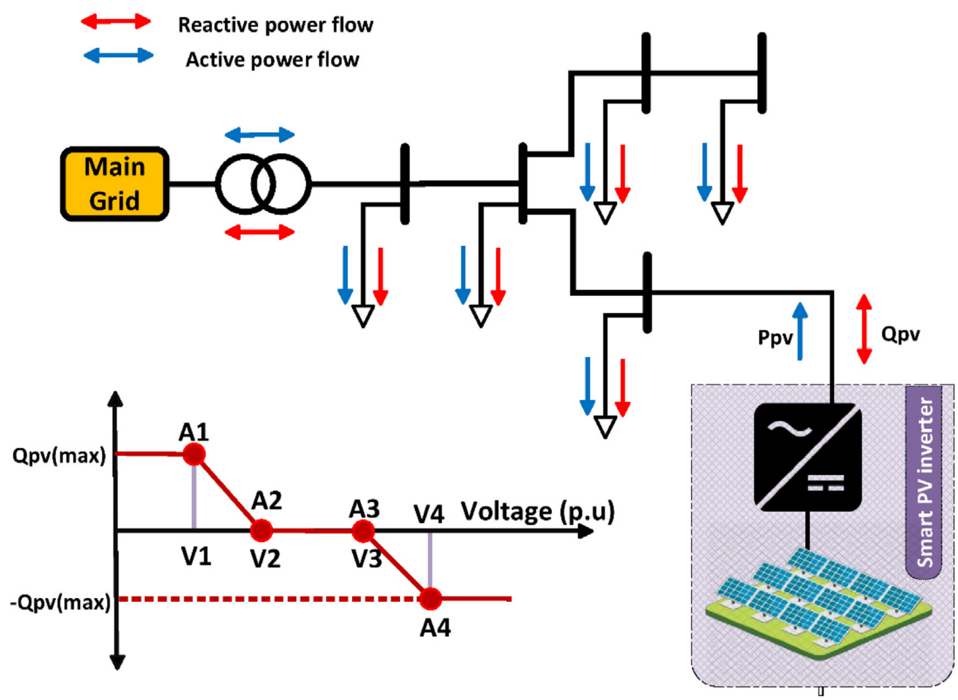
3.1. Smart PV inverters for active and reactive power control

The high penetration of photovoltaics (PVs) in distribution networks may result in voltage fluctuations and violation issues. To overcome these problems, the active and reactive powers of PVs are controlled by smart inverters. Fig. 11depicts the line diagram of a smart inverter integrated into the distribution network. Smart inverters have two basic functionalities. To begin with, the active power generated by PVs is converted from DC to AC. In addition, the extra rating of inverters are used to absorb/inject reactive power into the network.

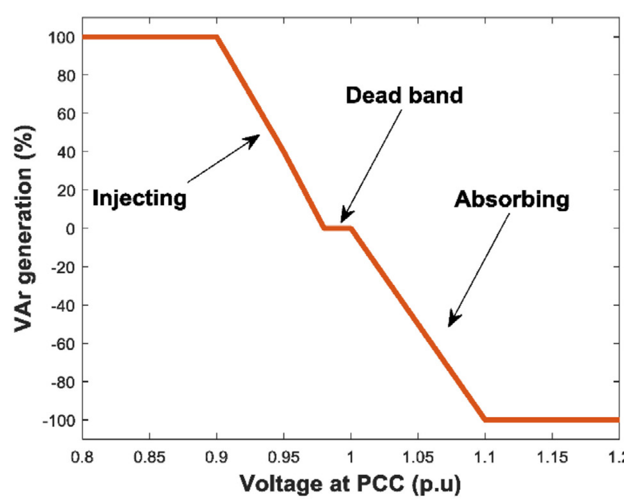
Authors in Gush et al. (2021) proposed optimal reactive power control approaches for smart PV inverters and energy storage systems (ESSs) to enhance the PV hosting capacity in distribution grids. To this end, the location, sizing and scheduling of PVs and ESSs were simultaneously determined by evolutionary algorithms with the aim of minimizing the voltage deviation and maximizing the PV hosting capacity. The results showed that the combination of PVs and ESSs is a viable solution compared to conventional methods such as tap switching/capacitor banks. In addition, an effective short-term planning strategy for minimizing the energy loss of distribution grids with PV inverters was provided in Alkaabi et al. (2019). From this research, it could be seen that PV inverters are better alternatives to support the reactive power of system and voltage regulation when comparing with other conventional methods like capacitor banks. This is because it is more adaptable, and flexible which in turn leads to significant energy saving and faster voltage regulation. Researchers in Doan et al. (2020) focused on the use of PV inverters and ESSs for VAR control in distribution systems. A two-way mechanism consisting of voltage and power modes was provided for voltage regulation and power loss minimization based on the operator preferences. The proposed method gives a flexible degree of freedom to the operator (voltage regulation/power loss minimization) under real-time operations. A local management approach for the active/reactive power of PV inverters was developed in Ceylan et al. (2021) with the aim of voltage regulation in distribution networks. To this end, a sensitivity-based droop control was provided and compared with the existing droop control (IEEE-1547). It can be concluded from this article that the proposed method is robust enough to deal with voltage control in distribution grids. Although the above mentioned investigations represent significant solutions for voltage control in power grids, some device operations such as OLTC were not altered enough, thus making them quite complex. To illustrate that, A bi-step method in Emarati et al. (2021) was proposed for the voltage control in a distribution network integrated with PVs and ESSs. In the first step, OLTC and ESS are scheduled for controlling the voltage at the peak of PV generation and the voltage drop in the peak of demand. The reactive power of the network is compensated via PV inverters in the second step. Similarly, in Zhang and Xu (2020), a new index entitled load-weighted voltage deviation index (LVDI) was developed for checking the status of voltage deviation in the distribution network under the uncertainties of load and generation. The problem was formulated as a multi-objective approach and solved with the aim of reduction in voltage deviation and power loss. It is obvious that the introduced index has a beneficial impact on the voltage control in distribution grids. In addition, the problem was solved in two steps, where the OLTC and capacitor switching is set in a day-ahead scheme. On the other hand, in the intraday stage, the reactive power of PVs is scheduled. Fig. 12 illustrates the bi-step multi-objective approach for voltage reduction and power loss minimization. If we have a closer look, this bi-step approach is a great way to have more precise results because at day-ahead stage the optimization is executed to find the optimal tap switching positions of OLTC and CB. In the intraday step, just smart inverters are scheduled to eliminate the probabilistic voltage violations.

Arbitrarily, central and local voltage/var control schemes have been separately obtained. However, the research in Zhang and Xu (2020) used a hierarchically-coordinated approach to obtain a collaboration between central and local controls. Central hierarchy dispatches the output of reactive power of smart inverters while local operators have a tendency to control the voltage of the network. This method outperforms other prior methods in terms of minimizing the power loss and the voltage deviation. Fig. 13 shows the hierarchically-coordinated approach to have a collaboration between central and local controls.

An investigation in Malekpour and Pahwa (2017) was provided for the effective control of reactive power of smart inverters in order to enable higher penetration of rooftop PVs in distribution systems. The inverters were controlled under three conditions. When the variation of solar irradiance is slow (normal condition), the inverter is controlled to reduce the power loss as an ancillary reactive power supporter. On the other hand, under the high fluctuation of PV output (passing clouds), the smart inverters are managed to support the reactive power and decrease voltage fluctuations. The inverters' reactive power output is controlled to maintain the voltage within acceptable ranges when the voltage is violated. For instance, during the peak of PVs (overvoltage) and loads (voltage drop). Similarly, the on-line tap changer (OLTC) transformer was used in the presence of the smart PV inverter for reactive power compensation of the distribution systems in Ku et al. (2019). This method derives the tap position along with the reactive power control of smart inverters which in



(a)



(b)

Fig. 11. Smart PV inverter connected to the distribution grid: (a) the schematic of the smart PV inverter integration into the distribution grid and (b) example of a droop control characteristic for the smart inverter.

turn results in maintaining the voltage between the acceptable boundaries. Besides, the minimization of the voltage deviation and the number of tap operations were the objective of voltage control in distribution networks with photovoltaic inverters and OLTC in Li et al. (2020). A linearized power flow is also provided to decrease the computational burden. Implementation of the proposed approach to a 37-bus test network showed a significant decrease in voltage unbalance and voltage deviation.

3.2. Conservation voltage reduction (CVR) and load modeling

Generally speaking, CVR maintains the delivered power to the customers in the lower voltage boundaries by not interfering with the efficiency of electrical components at the users' end. In other words, the CVR can be considered as a term of an objective functions to decrease the total power consumption of the entire network while keeping a feasible voltage profile.

Considering the fact that CVR is a voltage control scheme, it hinges on the voltage dependency of loads to save energy. In order to have a reliable approach, CVR is executed in the presence of load models. Sometimes, the CVR is integrated with the load model.

To begin with the literature review, the authors in Arora et al. (2021) proposed a model for reducing the substation demand with CVR alongside smart PV inverters under different controlling functions, such as Volt-VAr, Volt-VAr-hysteresis, Volt-Watt, and

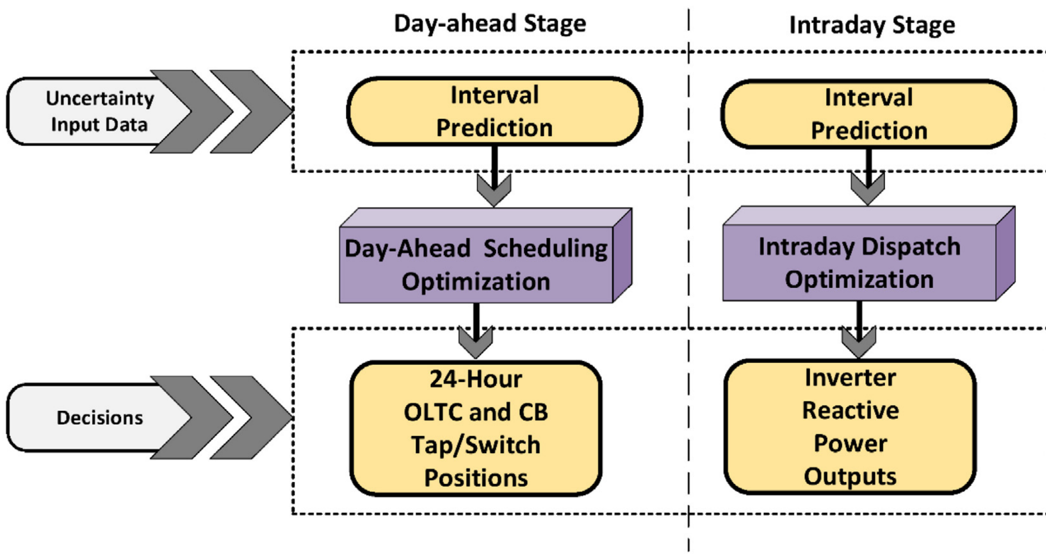


Fig. 12. The bi-step approach with the aim of reducing the voltage deviation and power loss.

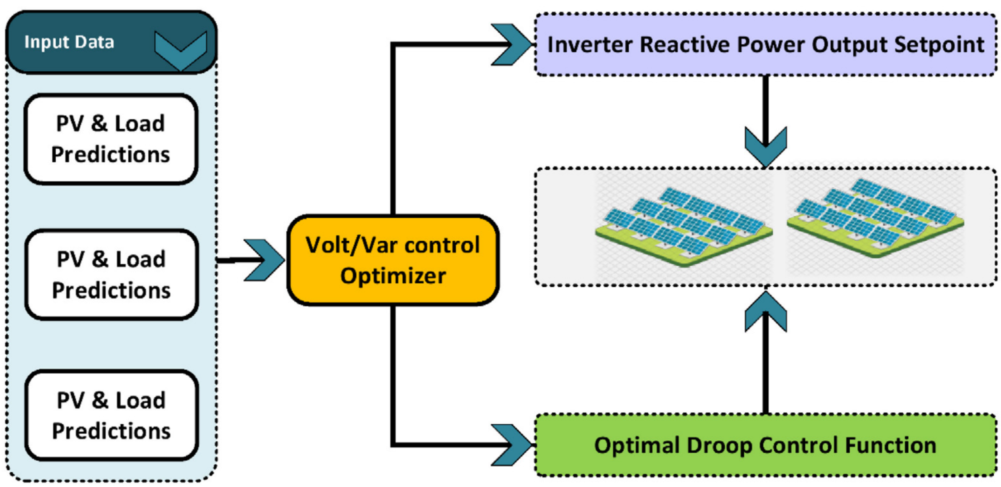


Fig. 13. Hierarchically-coordinated approach to have a collaboration between the central and local controls.

combine modes. Fig. 14 depicts the above mentioned controlling schemes for PVs. The PVs were also operated under sunny and cloudy conditions to stimulate the transient nature of PVs' outputs. The problem was formulated with the aim of minimizing the summation of demand and power losses. The problem was then solved under two conditions, including with/without PV inverters. These were implemented on two large-scale networks and the results showed that the smart PVs have beneficial effects on the demand reduction in substation compared to only CVR. In more detail, this approach, not only led to more energy saving but also yielded better performance in voltage regulation and substantial reductions in power losses.

In Hossan and Chowdhury (2020), an investigation was presented to combine CVR with demand response programs (DR), with the aim of contributing to energy savings in distribution grids. More generally, the price of purchasing power is the highest during peak periods. The loads are consequently shifted to off-peak to decrease the cost of buying power from the substation. In addition to its economic benefits, this strategy helps flattening the voltage profile over the time horizon. This voltage profile achieved by demand response helps the CVR to operate the system under lower voltage setpoints, i.e. OLTC tap is set to lower voltage, thus meaning deeper voltage reductions in the substation. Accordingly, more energy saving is obtained. Distributed generation resources, such as PVs and energy storages are also used in the presence of CVR and DR under their stochastic nature via scenario generation and reduction techniques. After executing this approach on the IEEE test system under three DR programs, such as time of use (TOU), critical peak pricing (CPP) and peak time rebate (PTR), it was found that a combination of CVR and DR is a win-win approach for both customers and utilities; which in turn has advantageous effects on energy saving and shaving peak demand. A CVR scheme, which seeks to reduce the power consumption by voltage reduction, is successfully implemented on low voltage (LV) networks. On the other hand, medium voltage (MV) networks witness a significant increase in power losses after performing the CVR schemes. Pareto-based particle swarm optimization algorithm was thus provided in Gharavi et al. (2021) to find out a trade-off between power consumption reduction and the increase in energy losses by simultaneously coordinating the volt-var devices such as OLTC, and capacitors. There is no doubt that load modeling has direct influences on the voltage management schemes, the ZIP load model (Z=constant impedance, I=constant current and P=constant power) was incorporated into the system in addition to the aforementioned devices. This

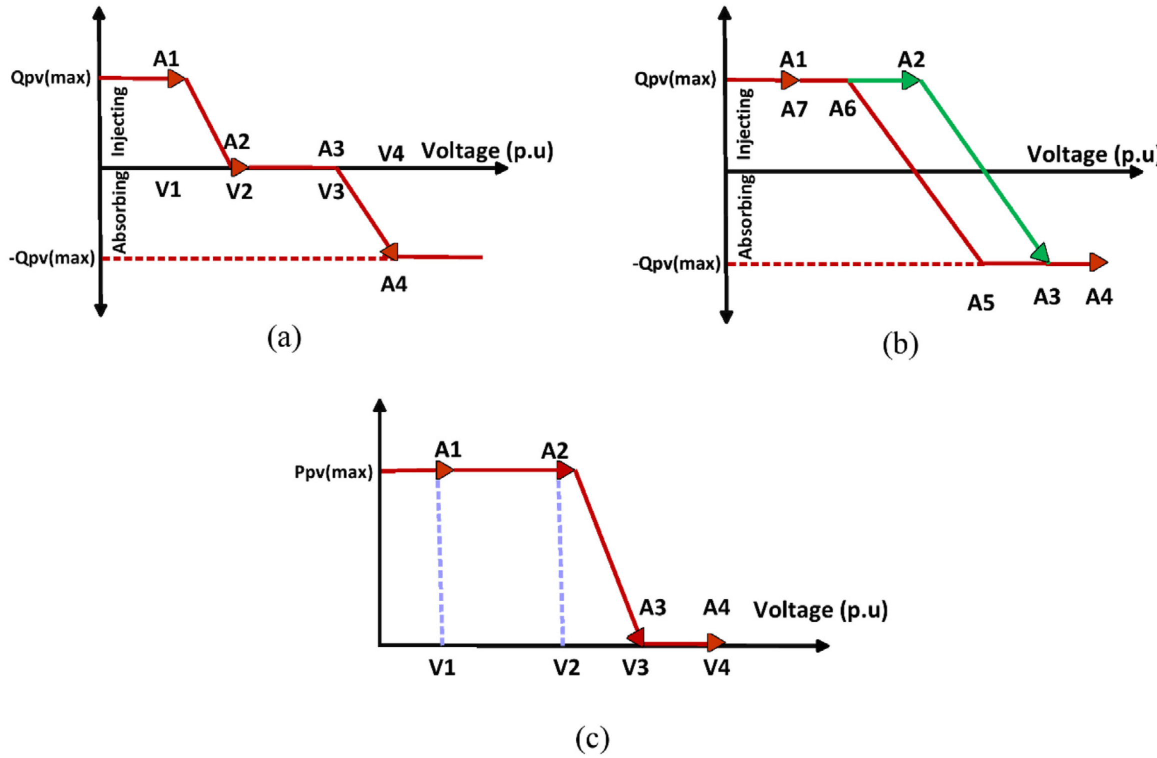


Fig. 14. The controlling mode of photovoltaic inverters: (a) volt-var mode, (b) volt-var (hysteresis) mode, (c) volt-watt mode (Arora et al., 2021).

method was carried out on both LV and MV networks and results were provided. It was shown that implementing CVR on LV networks provides more power loss reduction (twentyfold) than MV networks. Although CVR is widely used in decreasing energy losses, its interaction with PVs, which are inevitable parts of future grids, needs to be investigated. Due to the effect of PVs' penetration on the performance of CVR, a coordinated scheme was presented in (Cheng et al., n.d.) to assess this situation. To this end, the CVR was evaluated under allocation of PV units considering different penetration levels and control modes, IEEE Std 1547-2018. Besides, the voltage has a direct relation with voltage management, the ZIP model was used in this regard. Under different cases, it was shown that the optimal allocation of PVs improves the flexibility of CVR schemes, flatten the voltage profile across the entire networks, yields substantial power loss reductions in branches, and result in more energy savings. On the contrary, by introducing power electronic devices such as DVR, DSTATCOM, etc., extending the existing platforms with such technologies should be taken into account. By way of illustration, a coordinated planning of energy storage system (ESS) and soft open point (SOP) in PV-rich distribution grids considering DR and CVR schemes in Pamshetti and Singh (2020). This is formulated under a two-stage framework. During stage 1, the optimal location and size of BESS and SOP devices were determined concurrently. Stage 2, on the other hand, optimizes the operation of BESS and SOP under CVR and DR schemes. The objective function was formulated to minimize the cost of investment in BESS and SOP devices. The operational costs, including the purchased power, CO_2 emission and energy not supplied were also added into the objective function. Load and PVs uncertainties were also modeled by means of scenario generation via Monte Carlo simulation. Following this, k-means were used to find appropriate scenarios and solutions were derived using a hybrid evolutionary algorithm. Similarly, Pamshetti et al. (2021) investigated the Volt-Var optimization problem in distribution networks without considering demand response programs. Another difference is that the exponential voltage-dependent load model was used in Pamshetti and Singh (2020) while the ZIP model was chosen in Pamshetti et al. (2021). In general, the ZIP model is used to exhibit the load characteristics of the Volt/Var schemes. However, ZIP may not be applicable for the reason that utilities do not have access to the information of all feeders. The investigation reported in Singh et al. (2019) proposed a practical load modeling solution for cases when sufficient information about the users consumption is not available. To this end, an exponential model which considers the relation between CVR, power and voltage is utilized. In spite of modeling CVR in the load modeling phase, CVR was considered as a term of objective function. The electric vehicle under different controlling modes were also investigated in this paper. The approach resulted in more energy saving and additional power loss reduction.

In Paul et al. (2021), a volt/var optimization alongside the load shifting and CVR was proposed for hybrid AC/DC grids. The uncertainty of load, PV, and market price was modeled via a two-point estimation strategy which significantly decreases the computational burden. The reported results showed the approach to be quick enough for use in real-time executions. CVR is also capable of being implemented on home appliances to have much more energy saving. For instance, energy saving strategies for thermostatic loads (TLs) like air conditioner and refrigerator were investigated in Wang (2018). It was implemented on large-scale radial and meshed networks under various conditions comprising weekdays and weekends; weather conditions: hottest and average summer days during peak load of the year; load types: mixed load (ZIP and TLs) and ZIP load. The reported results showed that more energy savings are achieved when this method is implemented on meshed grids as opposed to radial systems. This is due to the fact that meshed grids use shorter cables and more transformers, whereas radial networks use fewer transformers and longer cables. As a result, in radial systems, cable losses outweigh transformer losses and conversely cable losses increase during CVR, while transformer core losses decrease. As

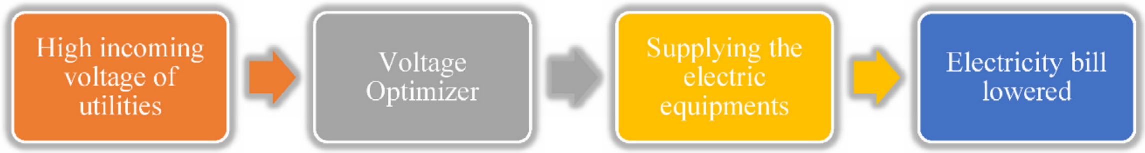


Fig. 15. The location of the voltage optimizer integration into the network.

a result, CVR is more effective in mesh networks. Furthermore, the implementation of CVR in a meshed system requires only a change in the setting of the substation transformers' on-load tap changers, whereas a radial system may require adjustments to voltage regulators down the feeders as well.

3.3. Voltage optimization (VO) technology

Distribution system companies (Discos) almost always maintain the voltage at the higher end of the standard limits to account for voltage drops at buses located a long distance from the substation. When this is not considered, customers would experience lower voltages and the network branches will exhibit increased power losses. Voltage optimization (VO) is a type of voltage management technique that adjusts and controls the voltage levels at the consumer side so as to decrease energy consumption. It means that the energy consumption of voltage dependent loads such as Metal Halide lamps, fluorescent lamps, and motors are altered according to how much voltage is received. Therefore, such loads typically benefit from voltage control in the form of lower energy consumption. The motors, for example, are not operated under full loads, meaning that roughly 70%–90% of their capacity is often used. Accordingly, when the motor needs a lower energy, the extra energy should be controlled by decreasing the voltage, i.e. 70%Pmotor = 70%V×I). VO brings substantial cost savings due to its advantages like better power quality, less maintenance of equipment, longer device life, and lower power consumption. However, VO may impose some technical and economic issues when loads are not sensitive to voltage. Fig. 15 shows the sitting of integration of voltage optimizer in the network. It is obvious that the voltage optimizer is directly installed at the high incoming voltage of the utility and then its output is used to supply the load demands. Due to keeping the voltage at the lowest acceptable range, the power consumption slightly decreases which leads to reducing the electricity bill.

In terms of the practical integration of VO in industries, few investigations have been done. For instance, the incoming voltage to equipment of meat processing facilities is higher than the optimal value. This in turn appears as ineffective utilization of energy, which causes overheating and shortening of equipment life. Thus, authors in Shafiullah et al. (2018, 2017) assessed the potential of VO technology on energy saving and power quality improvement in Australian abattoirs. A techno-economic assessment of VOs is also taken into account to recognize the appropriate VOs for the Australian meat processing sites. The obtained results showed that the feeder voltages were kept within the optimal levels, thus leading to sufficient energy saving. Additionally, the approach was shown to have an effective impact on other technical aspects like power quality enhancement (total harmonic distortion, THD, and over–under voltage), power factor improvement, power loss minimization, etc. In terms of technical issues, there are not any problems associated with not deploying VO in abattoirs. Fig. 16 illustrates the execution of the potential of VO technology on energy saving and power quality improvement. Note that the phase voltages, obtained prior to implementing the voltage optimizer technology, vary between 230 and 250 V, whereas the use of the VO resulted is significantly dropping the phase voltages to between 220 and 230 V and lowering the harmonics.

Similarly, in Brown and Fsadni (2015), an investigation was done to identify what impacts VO has on energy saving and emission reduction in healthcare and academic buildings. It shows that applying VOs to buildings has a significant reduction in power consumption (9%–13%) along with a decreased in the carbon emission (836 to 2250 kg CO2). Its positive impact was shown to increase when combined with renewable energies. The power consumption over 8 days is depicted in Fig. 17.

Despite its benefits, lowering the voltage results in an increase in current for constant power. This in turn rises the power loss and enlarges the size of cables. Accordingly, VO is not appropriate for buildings in which most utilization of electricity is consumed for heating.

3.4. Demand response programs (DRP)

Numerous power companies offer demand response programs (DRP) in which electricity consumers can participate and get money back for lowering their power needs at the utility's invitation throughout peak periods of consumption. Examples are attempting to turn up the temperature on a thermostat to minimize air conditioning burden, turning off certain lamps, or trying to shift the time of use of several energy-consuming machines out of peak demand periods. The load managed to avoid for a location may indeed be limited, but if numerous customers participate, the power company sees a significant decrease in energy consumption. The DRPs could be divided into two main categories, including incentive-based rates and time-based rates (Oconnell et al., 2014). These also have several subcategories, as shown in Fig. 18.

Note that, incentive programs possess 6 groups named direct load control (DLC), ancillary service market (ASM), interruptible/curtailable service (I/C), capacity market program (CAP), emergency demand response program (EDRP) and demand bidding/buyback (DB). DLC and ASM are voluntary programs, meaning that they are not penalized whether curtail consumption. A/S scheme enables the customers to bid curtailment of load as operating reserves in electricity markets. I/C and CAP are mandatory programs in which users who participate face penalties whether not curtailing the load when commanded. The DB program encourages sizable customers by providing load reductions at a price agreed to pay, or to identify what further load they are able to curtail at posted prices. In terms of time-based programs, there are three subgroups including time of use (TOU), critical-peak pricing (CPP), and real-time pricing (RTP). Time-based DRPs aim at shifting the demand from peak to off-peak, where the supply cost is lower. There is no incentive or penalty for time-based DRPs.

In low voltage (LV) networks, operators face over and undervoltage conditions due to high penetration of PV systems and electric vehicle fleets, respectively. Such resources lead to several problems in voltage regulations. To this end, demand response programs (DRPs) which shift flexible loads can be one of the most influential methods in voltage regulation schemes in distribution networks (Xie et al., 2020). In this investigation, a bi-step strategy was proposed for voltage management in the presence of flexible loads. Initially, there is day-ahead management that optimizes

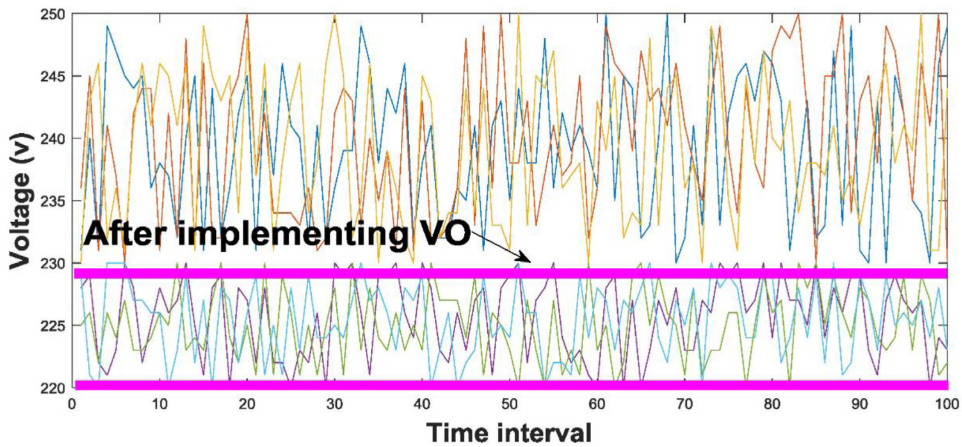


Fig. 16. The potential of VO technology on energy saving and power quality improvement.

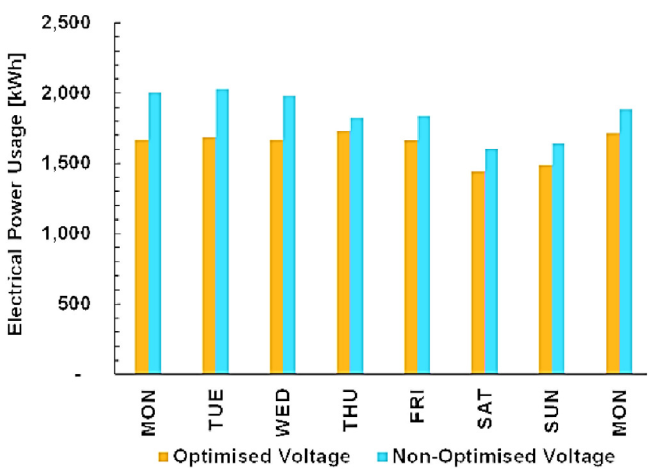


Fig. 17. The results of power usage in the presence of a voltage optimizer (Brown and Fsadni, 2015).

the commencement of flexible loads to alleviate the customer energy bills and system voltage violations. The second phase is a real-time operation framework, in which the shifting method of flexible loads is proposed to keep the voltage within the acceptable boundaries. Through the results, while the flexible loads are not scheduled or are only scheduled to minimize the energy cost, the OLTC requires 8–10 times functions to regulate the voltage between the standard limit. It is a challenging experience for DSOs because high OLTC steps should indeed be neglected. In comparison, if indeed the flexible load has been used through DR, the number of OLTC operations can be reduced to just one. This significantly reduces the DSOs' regulatory stress. DRP can also be used on the consumer side. In Zhang and Bao (2021), authors proposed a model to equivalent thermostatically controlled loads such as air conditioners as energy storage for voltage regulation of distribution levels. In other words, the thermostatically controlled loads which are installed on the customer side were utilized as a device to participate in voltage controls. Accordingly, such loads were considered as constraints of problem formulation to minimize four objective functions including demand response cost, power loss, voltage deviation, and voltage overrun penalty. Through the results, it is obvious that voltages are maintained within the safe boundaries whether thermostatically controlled loads participate in decreasing voltage fluctuations. In order to illustrate the advantages of DRPs on practical systems, it should be implemented in a real case study. Therefore, the smart grid technologies of DRP and Volt/Var Control (VVC) are incorporated in a power distribution grid in Solanki et al. (2012). The Multi Agent System (MAS) is utilized to construct the coordination scheme through the real-time communication of electric grid models. The impacts of the coordinated strategy on various voltage sensitive load models for voltage profile, electricity consumption, losses, and reactive power have been explored. Through the results, it was clear that simultaneous integration of DRP and VVC under real-time execution can result in significant demand reduction due to node voltage reduction, and demand curtailment throughout the time frame. On the same track, researchers in Venkatesan et al. (2012) tried to model the behavior of users on volt-var control schemes. They have developed an extensive demand-price elasticity matrix for different consumers. It was implemented on a large-scale IEEE 8500-node network under different case studies. Through the simulation results, DRP was shown to have a significant impact on voltage profile enhancement because of further demand curtailment, particularly within peak hours. Integration of DRP with other conventional voltage control devices, e.g. OLTC, VR, CBs, and so on is also another challenge which is addressed in the following investigations. The authors of Anderson and Narayan (2011) demonstrated how DRP may be leveraged to ensure a flatter and stable voltage profile across the grid without expanding the deployment of voltage regulators and shunt capacitors using a novel network simulator, GridSpice. The enhanced voltage level offers a safe voltage reduction while keeping all loads inside the allowable operating boundaries. Prior research suggests that lowering the load voltage causes a decline in electric bills, a concept called conservation voltage reduction (CVR). Through deploying CVR, researchers demonstrated that DRP helps to flatten bus voltage thus increasing network performance. A research published in Chandran et al. (2020) also employed a coordinated DRP incremental curtailment mechanism to control the voltage profile of LV distribution grids. A 74-house distribution system was considered as a test system to examine its voltage profile under various degrees of loads and PV integration. With rising loads, grid voltage levels drop as one moves away from the distribution substation, but with DG penetration, the voltage profile is markedly better managed. However, higher DG generation causes overvoltage in the system. When there is under-voltage, a DRP is used to lower the customer consumption depending on the engagement plan selected by the consumers. To reflect the extent of discomfort that a customer must bear whilst engaging in a demand side management, the integrated strategy employs a tolerance value. Briefly, the conjunction of DRP and Volt-Var techniques effectively manage operational voltage profile of the

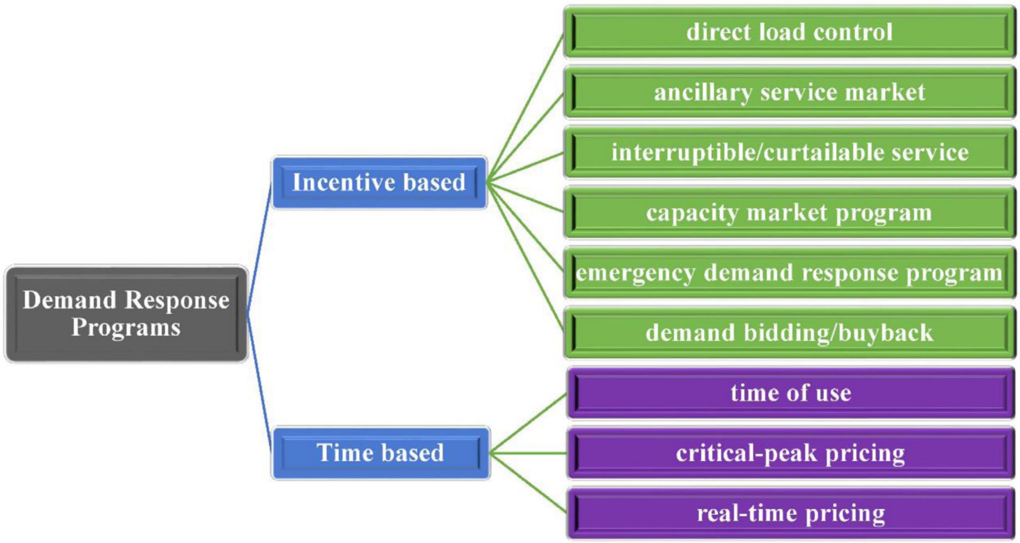


Fig. 18. Classification of the demand response programs.

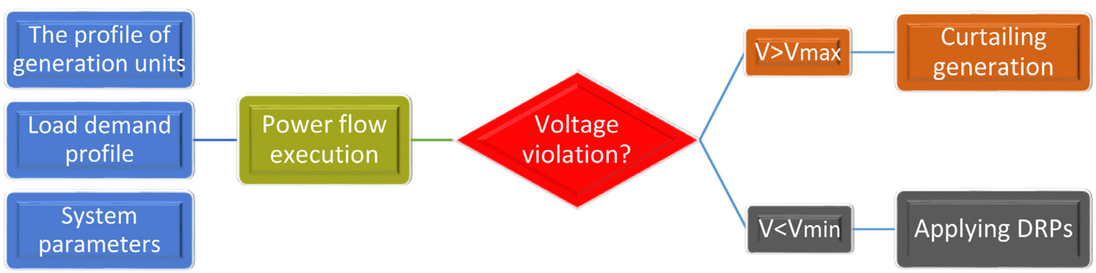


Fig. 19. Voltage control procedure by DRP and generation units.

distribution network by directly involving consumer resources (load and generation). Both customers and Discos take benefit from the method. Fig. 19shows the steps of the coordinated DRP incremental curtailment mechanism to control the voltage profile of LV distribution grids.

In the above procedure, power flow is firstly executed on the available power generation systems and voltages of different buses are obtained. If the voltages are higher than their acceptable ranges, the generation of the local resources are curtailed. However, when voltage levels are lower than the acceptable ranges, a demand response is implemented. This ensures maintaining the voltage values within their standard limits.

A real-time voltage regulation under emergency situations was described in Zakariazadeh et al. (2014). In that work, it was shown, analytically, how demand curtailments in a power grid caused by DRP could alter the voltage profile of distribution networks. The proposed real-time voltage control method was able to maintain the distribution voltages within their acceptable limits in emergency situations. Load curtailment sensitivity matrices were also built to assess the impact of load change on bus voltages. The findings demonstrated that decreasing demand via the suggested strategy helps minimizing the under-voltage over all feeders of the system and attempting to create a voltage rise at the buses having a long distance to the substation.

Researchers in Vijayan et al. (2021) proposed a day-ahead optimization approach for unbalanced distribution networks that takes into account DRP to relieve peak demand, volt-var control to decrease real power loss, and imbalance reduction. The objectives of this study were addressed by employing flexible loads, photovoltaic inverters, OLTC, VRs, and CBs. Unlike prior studies (merely considering scheduling of active power of loads), the suggested strategy includes scheduling of kVA loads, which also affect the functioning of volt-var equipment. The proposed problem formulation, which is handled through MOPSO every 15 min, drastically decreases peak load, power losses, and substation imbalance rates. From the results extracted from two networks, the peak load of the IEEE 13-bus and the 123-bus networks decreased by 10 and 7.5 percent, respectively. Energy loss can be reduced for both networks, outperforming the basic case and the CVR technique. In spite of producing superior results, the suggested structure converges with tight voltage limitations and prevents power curtailments. The efficacy of this customer-driven strategy under severe loading situations demonstrates that it is a superior option to popular solutions such as CVR. Rahman et al. (2018) described a novel suitable approach for voltage regulation in unbalanced distribution systems on the basis of optimum execution of residential demand response (DR) and OLTC. The aim is to reduce the compensation costs of voltage control (cost of DR and network loss), while prioritizing customer consumption preferences to avoid comfort level violations. A modified version of the PSO algorithm was used to determine the optimal switching arrangement of residential appliances and OLTC tap positions for network voltage control. The suggested technique was thoroughly tested on a practical Australian LV grid with significant unbalanced and distributed generation units. Several scenarios are studied in order to improve system voltage levels and imbalance. The experimental findings indicated that the coordination of DRP and OLTC brings various advantages, such as enhancing voltage profile, maximizing the hosting capacity of PVs, enhancing voltage imbalance while lowering the total cost

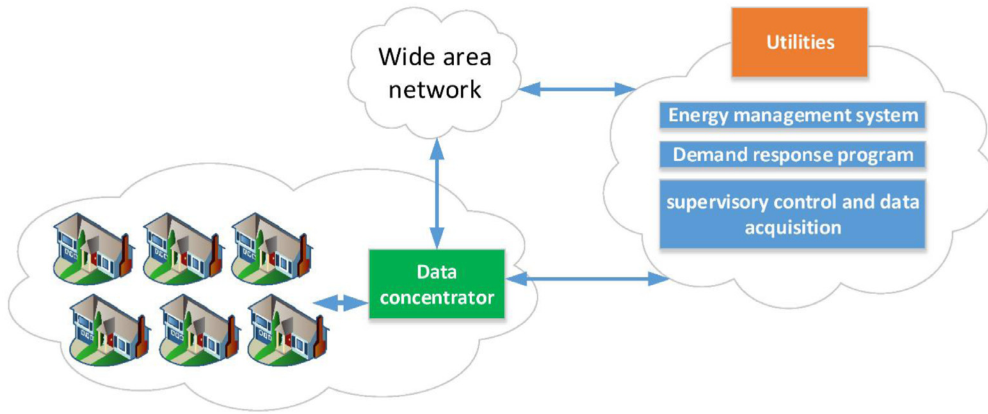


Fig. 20. The smart grid platform for implementing demand response (Rahman et al., 2018).

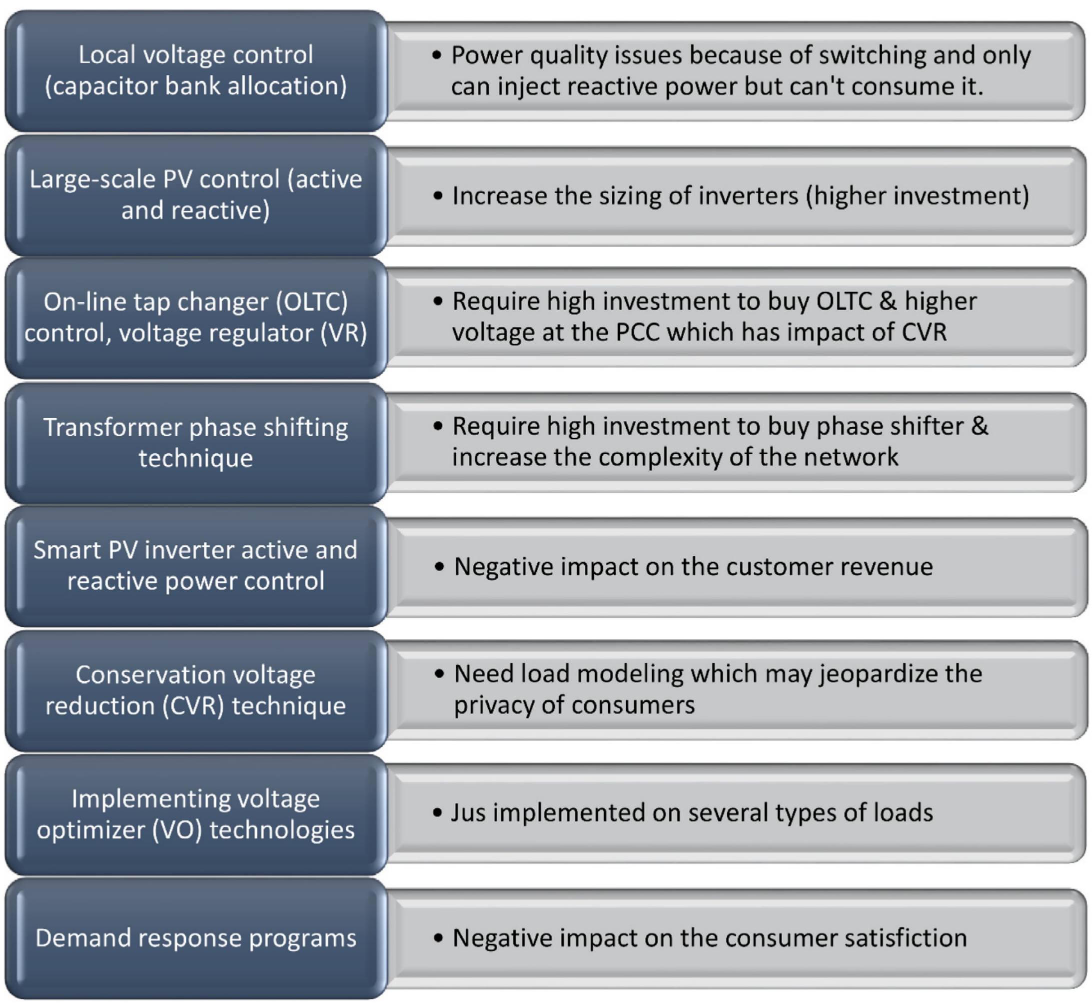


Fig. 21. Summary of the limitations of the volt-var control technologies investigated in this paper.

of compensation and consumer comfort level violations. Fig. 20 shows the overview of the communication infrastructure under the smart grid. As can be sent, the residential loads have a bidirectional communication with the utilities by wide area network and data concentrator. This communication can be used to easily implement a demand response program.

4. Summary and future works

The electric networks encounter many challenges, including aging infrastructure, continuous demand growth, the incorporation of more solar and wind power, requiring better security and sustainability, and reducing greenhouse gases. Smart grid technologies provide solutions not only to such obstacles, but also from the development of a greener energy production that is more reliable, convenient, and economically sound. The smart grid features have the potential to boost utilization, stability, standardization, and privacy of the electric networks. Voltage management in the distribution network is becoming more important due to the high penetration of distributed generation resources. This involves some challenges for operators to securely operate such networks. To this end, various techniques have been presented in this paper to deal with such challenges. These comprise capacitor banks, on-line tap changer, voltage regulators, Transformer phase shifting, smart PV inverters, Conservation voltage reduction (CVR), voltage optimizer technology, demand response, and load modeling. Although each mentioned method has its advantages, there are some drawbacks associated with them. Some of the important limitations are highlighted below:

- Capacitor bank allocation: it is listed as a frequently used technology since it is cost-efficient. However, it has some drawbacks, e.g. power quality issues, maintenance cost, not being as flexible as PV inverters and could be merely set in a few steps. It should be noted that the capacitor bank just absorbs reactive power and cannot inject reactive power. This traditional volt-var control device will be replaced by the new smart grid devices like smart converters for solar PV and wind in the near future for the volt-var control in the distribution networks. However, due to the recent growing penetration of the large scale renewable penetration into the grid has increased the use of the capacitor banks as harmonics filters to sink the high frequency harmonics injected by the smart inverters.
- Large-scale PV control: this is a great remedy to harvest higher decolonization. The grid codes of most countries require large scale PV inverters to have enough capacity to provide a fast reactive power support to the grid. The fast current controllers of these smart inverters have the fast volt-var control capabilities, which can response faster than the traditional volt-var control devices such as capacitor banks, voltage regulators, etc., in the network. In near future, the smart inverters will be a dominating technology to control volt-var in the distribution grids. Nevertheless, the large-scale PV plant has an exorbitant expenditure such as investment on lands, higher inverter rating, meeting grid connection challenges, etc.
- On-line tap changer (OLTC) and voltage regulator (VR): these equipments have been used frequently in conventional networks, where all the demand was supplied unidirectionally by the power plant. However, they may not be a promising technique to control voltage in a smart grid because of not having fast response under real-time implementations. Not only do these technologies require high investment costs, but also require coordination control with other devices in the network for proper voltage control. For example, OLTC can pose barriers on CVR implementation.
- Transformer phase shifting technique: the application of this device may be rare compared to others, due to requiring high investment to buy phase shifters and increase the complexity of the network, which means the numbers of controllable variables are increased. In other words, the absence of transformer phase shifting can be easily addressed by new electronic-based technologies which are more precise and promising controlling.
- Smart rooftop PV inverter active and reactive power control: although this technology has a great impact on improving the efficiency of the network, like power loss minimization and local voltage control, it has a negative impact on the customers' revenues.
- Conservation voltage reduction (CVR): this is not equipment, and is implemented alongside other methods, particularly entails the load modeling schemes. CVR is one of the alternative techniques that can be used to manage the voltage in the distribution network in coordination with the network equipment. With the proper coordination control, the CVR can accommodate high penetration of renewable generations as well as load demand without further investment on the network upgrades. The main barrier of the CVR implementation is to accurately model the loads in the network, which is quite complex particularly for the residential sector.
- Load modeling: this does not change the voltage level, but is just used along with the above mentioned voltage control methods for increasing their penetration into the network. It is important to note that this strategy may not be executive in all areas, because of keeping privacy of users and numerous load types. Different load types show different behaviors during steady state and dynamic voltage changes in the network. Thus, it requires various load modeling studies to capture the effects on the network voltage change.
- Implementing voltage optimizer (VO) technologies: this method is a great way of decreasing the electricity bills by reducing the local voltage for particular types of load demands. It means it cannot be implemented for all load types like controllable motors, etc. In more detail, system infrastructures have to be upgraded if the loads do not have the capability of supporting VO. For example, for a load with constant power, the size of cables must be increased if the voltage decreases. This is because by decreasing voltage, the current needs to increase to provide the required power of equipment. Accordingly, this technology is not applicable to implement in all kinds of load types and utilities should not invest on this technology due to the fact that accessing the data of consumers may be jeopardized.
- Demand response (DR) programs: it is ranked as new technologies which help distribution system operators to take some technical/economic advantages, i.e., congestion relief and voltage control. It allows the consumer to receive rewards when participating in such schemes. On the other hand, it possesses a negative impact on the customer satisfaction because of postponing their load demands to specific times, such as off-peak hours.

The above drawbacks are illustrated in Fig. 21.

Tables 1 through 7 also summarize all the studied papers related to volt-var control by highlighting the technologies used for volt-var control, objective function, advantages and disadvantages of the volt-var technologies.

Several topics are still open which are listed as follows:

- Effective integration of direct load control demand response in distribution grids under high penetration of renewable energies and energy storage systems is a challenge which needs further investigation.
- Electric vehicle charging stations will also play a main role in future distribution networks. When electric vehicles are integrated into system, the power quality issues, i.e, voltage unbalance, voltage decrease may increase. This situation may get deteriorated due these are under uncertainty. Therefore, voltage control of unbalanced reconfigurable networks which are under high penetration of electric vehicles and other RESs could be another open topic.
- Market has recently become one of the most important parts of the electricity industry. Due the main concept of the market is power trading, keeping voltage between acceptable ranges is essential. For example, under the bidding strategy of microgrids, volt-var should be investigated.

Table 1
Local voltage control with capacitor bank.

Ref.	Technologies utilized	Objective function	Advantages	Disadvantages
Ameli et al. (2017)	Capacitor switching network reconfiguration	Minimizing the cost of power purchase from the substation, cost of customer interruption penalties, transformer loss of life expenses, and the switching costs.	Using two cost-efficient technologies Considering a complete economic objective function	May not guarantee the global optimum. It may not be used in real-time implementations.
Islam et al. (2021)	Simultaneous allocation of energy storage systems and Capacitor Banks	Decreasing the voltage drop	combined ESSs and CBs are a reliable solution for coping with the vulnerability of the system to the voltage drop.	High investment on energy storages
Shaheen and El-Sehiemy (2021)	CBs allocation	Minimizing the power loss, investment of CBs, and voltage deviation.	Significant reduction of the economic objective function, at 20–25 k$/year. Improved technical aspects like voltages.	Time consuming and suffering from the finding global optimum
Singh et al. (2020)	Allocate the distributed generations and capacitor banks in the presence of on-line tap changer transformers	Minimize the cost of annual energy loss and node voltage deviations	Superior in terms of planning such devices in the distribution networks because of finding better solutions	Time consuming and suffering from the finding global optimum
Navesi et al. (2022)	Switchable CBs network reconfiguration renewable energy integration	Power loss minimization and voltage deviation reduction.	The coordination of CBs in the reconfigurable grids leads to the secure operation of the system.	Time consuming and suffering from the finding global optimum
Gholami and Parvaneh (2019)	DGs and CBs allocation	power loss minimization and voltage enhancement.	Better functionality from the algorithm, which means the less power loss and better voltage profile	Time consuming and suffering from the finding global optimum

Table 2
Large-scale PV control (active and reactive).

Ref.	Technologies utilized	Objective function	Advantages	Disadvantages
Karbouj et al. (2021)	Solar PV inverters, extreme weather conditions	–	The reactive power delivery by PV inverters was examined under extreme weather conditions. It was tested on two practical cases.	Did not consider the DC voltage of the inverter while optimizing the reactive power. Higher the DC link voltage, lower the active and reactive capability.
Wang et al. (2018)	Step voltage regulators, large-scale PV plant	Voltage problems and SVR tap operations	Less number of SRV tap operations and limited reactive power capacity.	Not implemented on a large-scale network
Resch et al. (2021)	PV and battery	Investment on integration of PV inverters	PV-ESS systems are introduced to defer the cost of traditional expansion planning schemes.	PV systems may take lands that may not be applicable in mountainous places.
Gao et al. (2019)	Hybrid AC/DC grids, power electronic transformer, PVs	The investment cost and power loss minimization	Less operational cost as well as less PV curtailments.	Protection issues and lavish cost of power electronic transformer
Valverde et al. (2019)	System operator, solar PV inverters	–	Support the reactive power of transmission networks	It needs a decentralized framework and may suffer from cyber securities.
Ruan et al. (2020)	SVC, wind turbine, PV inverters, OLTC	Both network losses and bus voltage deviations are minimized	A finite number of iterations, less complexity	It may not be applicable in ring networks.
Chamana and Chowdhury (2018)	OLTC transformers, CBs, SVRs, zone-based multistep scheduling	Minimize the PV curtailment and voltage deviation.	Less usage of regulators while minimal power output of PV inverters.	Rises the optimality gap which may not applicable, where exact results are vital.
Chang and Chinh (2020)	PV inverters, OLTC	Total system power loss and voltage regulator tap changes	Possibility to find appropriate solutions with faster convergence.	Using meta-heuristic algorithms increases the complexity of the problem.

- The potential of DFACT devices, such as DSTATCOM, unified power quality conditioner (UPQC), etc., in volt-var schemes should be investigated in distribution grids under harsh uncertainties of RESs.
- Decentralized volt-var control for multi-microgrid systems under the reactive power support of smart inverters is another topic which needs to be addressed to keep the privacy of all microgrids.

Table 3
On-line tap changer control, voltage regulator and phase shifting transformers.

Ref.	Technologies utilized	Objective function	Advantages	Disadvantages
Tewari et al. (2021)	OLTC, BESS, PVs	Minimize the voltage deviation	Superior to voltage regulation and resource utilization	Uncertainties could have been added.
Ali et al. (2021)	OLTC, reactive power of PV inverters, and EVs.	Probabilistic bi-step model is proposed.	It includes various voltage control devices	Using stochastic may impose the time consumption.
Zafar et al. (2020)	Coordinates the OLTC	Stability-constrained volt/VAR control scheme	Power loss minimization and reliable operation	Lack of robust uncertainty modeling
Chen et al. (2019)	DGs, OLTC, CBs	Optimization approach using niche genetic algorithm, a day-ahead plan, and dispatch plans.	Using fuzzy membership to have a balance between two objective functions, loss and voltage deviation.	Issues in real-time implementations due to its time consumption.
Tshivhase et al. (2021)	OLTC, VRs, DGs, and ESSs.	Voltage deviation minimization	A new coordinated strategy	Difficulty under real-time operations.
Azarnia and Rahimiyan (2022)	Uncertainty of load and resources	Lower operational costs and power losses	Robust and less computational burden	Not consider the ESSs, electric vehicles, etc.
Li et al. (2018)	OLTC, solar PVs	Minimizing the number of OLTC switching and voltage deviation.	Lower computational burden and higher PV accommodation	Lack of utilization of energy storage systems.
Olatunde et al. (2020)	OLTC, CBs, and ESSs	Minimizing voltage deviation, power loss, and improving voltage stability	Decreases more power loss and improvement of voltage profile	Implementing on balanced network may not be more realistic
Ding et al. (2017)	Phase shifting transformers	Embedded optimal power flow problem	Technical and economic benefits	High price and decreases lifespan
Ashpazi et al. (2015)	Phase shifting transformers	Optimal sizing and phase shifting transformers	Better stability of the system	Missing volt-var technologies
Qiao and Ma (2020)	OLTC and CBs are scheduled every 2 h	Loss reduction and voltage improvement	Sources are scheduled every 30 min for fast response	Complexity of the system increased
Kim et al. (2017)	The reactive power dispatch of DGs along with switching OLTC and CBs	Power loss minimization as well as decreasing the number of switching of OLTC and CBs	Support the reactive power	More time consumption
Ma et al. (2021)	Coordinating OLTC, CBs, and PVs.	Power loss minimization	A multi-objective framework was developed. The uncertainties were modeled.	Energy storage was not considered. May decrease the capacity to deal with real-time implementation.

Table 4
Smart PV inverters for active and reactive power control.

Ref.	Technologies utilized	Objective function	Advantages	Disadvantages
Gush et al. (2021)	Reactive power controls	Minimizing the voltage deviation and maximizing the PV hosting capacity	The combination of PVs and ESSs is a viable solution	Higher investment
Alkaabi et al. (2019)	PV inverters	Minimizing the energy loss of distribution grids	Energy saving and faster voltage regulation	Higher investment compared
Doan et al. (2020)	Use of PV inverters and ESSs	Voltage regulation and power loss minimization	Significant effects on voltage control	Either voltage control mode or power loss minimizations mode
Ceylan et al. (2021)	PV inverters	Voltage regulation in distribution networks	Robust enough to deal with voltage control in distribution grids	Volt-var techniques were not considered
Emarati et al. (2021)	PVs and ESSs	Voltage control	Leads to the least time consumption	Missing robust modeling of uncertainties
Zhang et al. (2020)	Uncertainties of load and generation	Reduction in voltage deviation and power loss	A new index entitled LVDI was developed	Two steps and a day-ahead scheme
Zhang and Xu (2020)	PV inverters, and OLTC	Minimizing the power loss and the voltage deviation	A collaboration between central and local controls	Robust uncertainty modeling
Malekpour and Pahwa (2017)	Rooftop PVs' inverters	Inverter is controlled to reduce the power loss as an ancillary reactive power supporter	Several adaptable control modes for different conditions	May not be fast enough to have a great response
Ku et al. (2019)	OLTC transformer, PV inverters	Keeping voltage between acceptable ranges	Keeping the voltage between the acceptable boundaries	This does not consider the uncertainties
Li et al. (2020)	PV inverters and OLTC	The minimization of the voltage deviation and the number of tap operations	A linearized power flow and voltage deviation experiences a significant decrease	Missing ESSs

Table 5
Conservation voltage reduction and load modeling.

Ref.	Technologies utilized	Objective function	Advantages	Disadvantages
Arora et al. (2021)	Smart PV inverters	Minimizing the summation of demand and power loss	Energy saving and better voltage regulation	Not appropriate under real-time implementations
Hossan and Chowdhury (2020)	PVs and energy storage in presence of CVR and DR	Reduction of power consumption by voltage control	Energy saving and flattening voltage profile over the time horizon	Time complexity issue
Gharavi et al. (2021)	Coordination of volt-var devices, ZIP load modeling	A trade-off between power consumption reduction and the increase in energy losses	More power loss reduction than MV networks	All utilities do not access the loads of consumers
Cheng et al. (n.d.)	PV units, ZIP load model	Energy saving, including power loss minimization	Flatten voltage profile across the networks and more energy saving	Under voltage problems
Pamshetti and Singh (2020)	BESS, SOP in solar PVs, Demand response program	Determination of the optimal location and size of BESS and SOP devices and the operation of BESS and SOP under CVR and DR schemes.	Minimize the cost of investment on BESS and SOP devices.	Operators need quick decisions
Pamshetti et al. (2021)	Exponential voltage-dependent load model	Different volt-var technologies are considered which leads to have a complete version.	Increasing the restored active energy, reducing the energy loss and energy consumption	Not be applicable for the reason that utilities do not have access to the information of all feeders
Singh et al. (2019)	Voltage regulator CBs, PV inverters Electric vehicle	CVR	More energy saving and power loss reduction	A robust approach to model the uncertainties instead of stochastic framework
Wang (2018)	TLs like air conditioner and refrigerator	Under various conditions comprising weekday and weekend; weather conditions	More energy saving is achieved	Some customers may not able to participate in this strategy

Table 6
Voltage optimization technology.

Ref.	Technologies utilized	Objective function	Advantages	Disadvantages
Shafiullah et al. (2018, 2017)	Voltage optimizer	Energy saving and power quality improvement in Australian abattoirs	Leads to sufficient energy saving and has an effective impact on other technical aspects like power quality enhancement	Enlarges the size of cables, not appropriate for buildings whose most utilization of electricity is consumed for heating
Brown and Fsadni (2015)	Voltage optimizer, OLTC, PVs	Impacts VO has on energy saving and emission reduction in healthcare and academic buildings	Significant reduction in power consumption, decreased the carbon emission	Lowering the voltage results in an increase in current for constant power

5. Conclusion

This paper provides a comprehensive review of existing volt-var control approaches. Based on our bibliographical review, we could draw the following conclusions:

The capacitor bank is a great way for controlling the voltage in distribution systems because it is a cost-efficient device. However, it has several drawbacks compared with smart PV inverters. To begin with, CB is not as flexible as smart PV inverters and may bring power quality issues due to switching. PV inverters are a bi-directional device so they can absorb and inject reactive power while CBs just absorb the reactive power. This means the inefficiency of CBs in controlling the overvoltage in the system.

Despite the benefits of voltage optimizer (VO), decreasing the voltage level in networks results in an increase in current for constant power. This in turn raises the power loss and enlarges the size of cables.

Demand response (DR) programs need to encourage the participation of consumers to participate in the network volt-var events. The complexity of DR is quite high particularly in the residential sector, which requires complex incentive mechanisms to reward the participants.

CVR is also a method which is used in the presence of other aforementioned methods, particularly, load modeling. However, the privacy of consumers is also important and some operators do not have access to users' consumptions.

OLTC is also a traditional scheme in voltage control, however, its action is frequently changed because of the high intermittent nature of renewable energies. These operational actions significantly decrease its lifetime. It is also not logical to change its step frequently due to the fact that it is not as fast as other techniques. It should be mentioned that it has a negative impact on CVR schemes, where we tend to decrease the substation voltage to save more energy.

To sum up, there is no doubt that all the reviewed technologies should be selected based on their merits and the nature of the power network to be considered. However, it is clear, from our review, that smart technologies such as PV inverters can provide fast volt-var control in distribution networks. Hence, we recommend using PV inverters instead of capacitor banks as an ancillary service to support the reactive power of the system. In addition, we recommend using demand response as a strategy to control the steady state voltage in power systems due to the fact that this strategy may not impose high investment capital cost like OLTC, battery, VR, etc and the potential for consumers to receive credit when they participate in demand response programs.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Table 7
Demand response programs.

Ref.	Technologies utilized	Objective function	Advantages	Disadvantages
Xie et al. (2020)	flexible loads	Minimizing the customer energy bills and system voltage violations	Significantly reduces the DSOs' regulatory stress	Not a complete strategy for load curtailment
Zhang and Bao (2021)	Thermostatically controlled loads	Demand response cost, power loss, voltage deviation, and voltage overrun penalty	voltages are maintained within the safe boundaries	Not implemented on loads like constant powers
Solanki et al. (2012)	DRPs	A coordinated method for DRP and VVC is devised and evaluated	Significant demand reduction and demand curtailment	Missing voltage optimizers and energy storages
Venkatesan et al. (2012)	DRPs	Extensive demand-price elasticity matrix	Voltage profile enhancement	Integration of DRP with conventional voltage control devices
Anderson and Narayan (2011)	DRPs	A safe voltage reduction	Flatten bus voltage, better network performance	Integration of DRP with conventional voltage control devices
Chandran et al. (2020)	Flexible loads and PV integration	A coordinated DRP incremental curtailment mechanism	Effectively manage the operational voltage profile	Not considered ESS to decrease the fluctuations of PVs
Zakariazadeh et al. (2014)	DRP, OLTC, Wind power	Alter the voltage profile of distribution networks	Minimizing the under-voltage over all feeders of the system	Not considered for unbalanced networks and smart inverters
Vijayan et al. (2021)	Flexible loads, PV, OLTC, VRs, and CBs	A day-ahead optimization approach for unbalanced distribution networks that takes into account DRP to relieve peak demand and volt-var control	Reduction of peak load of the networks and energy loss	Increases the computational burden
Rahman et al. (2018)	Residential DR and OLTC	Compensation costs of voltage control	Enhancing voltage profile, maximizing the hosting capacity of PVs, enhancing voltage imbalance	Increases the computational burden

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