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Review of Challenges and Research Opportunities for Voltage Control in Smart Grids

IEEE-PES Task Force on Voltage Control for Smart Grids

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Abstract—In this paper, we review the emerging challenges and research opportunities for voltage control in smart grids. For transmission grids, the voltage control for accommodating wind and solar power, fault-induced delayed voltage recovery (FIDVR), and measurement-based Thévenin equivalent for voltage stability analysis are reviewed. For distribution grids, the impact of high penetration of distributed energy resources (DER) is analyzed, typical control strategies are reviewed, and the challenges for local inverter Volt-Var control is discussed. In addition, the motivation, state-of-art, and future directions of the coordination of transmission system operators (TSO) and distribution system operators (DSO) are also thoroughly discussed.

Index Terms—Coordination, distributed energy resources (DER), distribution system operators (DSO), renewable, solar, transmission system operators (TSO), voltage control, wind.

I. INTRODUCTION

VOLTAGE control is facing significant challenges with the increasing integration of utility-scale wind/photovoltaic

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(PV) farms to transmission grids and various distributed energy resources (DER) in distribution grids. This is leading to major transformations of control schemes that require more sophisticated coordinations and interactions among controllers.

In transmission network (TN), there are many emerging challenges, including but not limited to voltage fluctuation, cascading tripping faults [1], and voltage stability issues such as fault-induced delayed voltage recovery (FIDVR). It will require a better understanding of the interaction between the existing TN and the renewable generation [2], advanced control methods that enable fast participation of renewable generation [3], computationally tractable approaches to help mitigate FIDVR [4], and also improved situational awareness about voltage instability through measurement-based approaches using phasor measurement unit (PMU) data [5].

In distribution network (DN), the high penetration of DER, such as wind or residential PV, has a very high impact on power quality, more specifically on voltage control [6], [7], which will be discussed in Section III-A. Although various control strategies have been proposed [8], [9], there are still many challenges that need to be addressed in the near future such as proper selection and trade-off of different control architectures, adequate parameter settings of local controllers, and the cost-effective coordination of a large number of DER to control voltages while minimizing generation curtailment.

In addition, due to the increasing coupling between the TN and DN, the transmission system operators (TSO) and distribution system operators (DSO) have to be properly coordinated for effective voltage regulation on both sides. This will be a major challenge as reactive power sources connected to the TN are replaced by DER in the DN, and will require more active participation of DNs on voltage support of TNs.

In order to tackle the above-mentioned challenges on voltage control in smart grids, it is urgently required a better understanding of the emerging problems, and more importantly, the development of more advanced voltage control methods. This paper presents a thorough review of the major challenges, different voltage control schemes that have been proposed to address these challenges, the coordinations between different voltage levels and control centers, and also potential research directions. This non-exhaustive review is based on the experience and concerns of the contributors of the IEEE-PES Task Force on voltage control for smart grids, and it serves as a basis to introduce the ongoing problems and future research

opportunities on voltage control.

II. VOLTAGE CONTROL IN TRANSMISSION GRIDS

Optimal voltage control has long been successfully implemented in TNs, including the three-level hierarchical automatic voltage control (AVC) in Europe [10]–[13], the adaptive zone division method in China [14], and the security-constrained optimal power flow (SCOPF) in PJM, U.S. [15]. The OPF-based formulations lead to solving challenging nonlinear, nonconvex problems that require the use of convex relaxation techniques [16], [17]. This topic has gained a lot of attention and future advances in this field are expected.

Facing emerging challenges such as large-scale wind/solar power integration, the voltage control method needs to be improved. Besides, it may not be sufficient to just maintain acceptable voltage profiles in the system. It is also important to maintain voltage stability that depends on proper volt/var control. Voltage instability includes both short-term and long-term aspects. Short-term voltage instability generally is related to induction motor stalling and is addressed in Section II-B. Long-term voltage stability is discussed in Section II-C.

A. Voltage Control to Integrate Wind Power and Solar PV

In TNs, one major challenge for high wind power penetration is the significantly increased risks of voltage fluctuation and cascading tripping. Fig. 1 shows the power and voltage of a wind farm named QLS during a typical cascading failure based on historical phasor measurement unit (PMU) data. To address this challenge, a hierarchical “autonomous-synergic” voltage controller is designed for the wind farm [2]. Three voltage control modes, *corrective control*, *coordinated control*, and *preventive control*, are proposed for different operational requirements: 1) Corrective control maintains the terminal voltage of wind turbine generators (WTGs) within their operational limits; 2) Coordinated control tracks the set value and mitigates voltage fluctuations considering all necessary operational constraints; 3) Preventive control reserves more fast-response dynamic reactive power (DRP), on the premise of maintaining the WTGs’ terminal voltages and the high-side voltage within a certain threshold.

In [18] reactive power resources are coordinated to enhance the voltage stability of grid-connected wind farms. Methods are also proposed to reserve more DRP in wind farms [19], considering the dynamics of wind farms by heuristic dynamic programming [20] or based on the PI-regulator for the wind farms’ secondary voltage control [21]. In [3], an autonomous wind farm voltage control based on model predictive control (MPC) is proposed to maintain the voltage within operational limits and maximize the DRP reserve. To deal with the high R/X ratio of the wind farm collector, a combined active and reactive power control is proposed based on MPC [22].

At system level, the mechanism of cascading trip faults has been analyzed [23]. Once such a fault occurs and propagates in wind farms, the voltage will significantly increase within 2–3 seconds. It is thus more reasonable for wind farms to take preventive controls [2]. The boundary of voltage security region (VSR) is computed by an approximate linearization method [24], [25]. Then a robust VSR [26] is proposed in

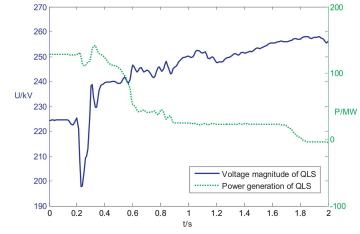


Fig. 1. Typical trip-off process voltage and power of a wind farm [2].

order to consider wind power forecast error. To determine an independent voltage control range for each wind farm, autonomous voltage security region (AVSR) is proposed [27]. In extreme scenarios with very high wind power penetration, insufficient DRP reserves may result in significant wind power curtailment. To address this challenge, an AVSR-based DRP reserve optimization is proposed so that wind power can be accommodated as much as possible [28].

Similar issues also exist for large-scale solar PV integration in TNs. A supervisory voltage control strategy is proposed in [29] to enhance the voltage stability in PV systems by a reactive current division algorithm and online supervisory coordination. In [30] the fault ride-through capabilities in utility-scale PV integration are enhanced using the overload capability of grid-tied inverters. A centralized sequence control strategy is designed to reduce the voltage unbalance factor and keep the PVs’ terminal voltages within a certain range by effectively utilizing the capacity of grid-tied inverters [31].

In addition, more wind power, offshore or onshore, has been connected to TN through HVDC lines. Compared with HVAC, HVDC operation is more complicated. The cascading trip faults caused by HVDCs such as by DC-blocking contingency is a major concern [32]. Addressing the local volt/var control complexity in DC converter stations will be challenging. Moreover, HVDCs have var regulation capabilities and can provide fast-response voltage support. Utilizing this to alleviate voltage control problems such as frequent adjustment of the discrete devices [33] is also an interesting topic.

B. Fault-Induced Delayed Voltage Recovery (FIDVR)

FIDVR issues are mainly caused by the stalling of air conditioner compressors due to low voltages. Their reactive power demand can increase more than 12 times until their internal thermal protection removes them from the grid [34].

The WECC/NERC planning standards have defined criteria on post-fault voltage recovery performance [35]. The percentage voltage deviation on bus $j = 1, \dots, N$ at time t for contingency k among K contingencies can be calculated as:

$$r_j^k(t) = \left| \frac{V_j(t) - V_j^{\text{init}}}{V_j^{\text{init}}} \right| \times 100\%, \quad (1)$$

where N is the number of buses and V_j^{init} is the pre-fault initial voltage magnitude of bus j . The following criteria are usually considered for the post-fault voltage trajectories:

$$S_1 : r_j^k(t) \leq R_1 \text{ for } t_{\text{cl}} \leq t \leq t_s, \quad (2)$$

$$S_2 : T_{r_j^k(t) \geq R_2} \leq D \text{ for } t_{\text{cl}} \leq t \leq t_s, \quad (3)$$

$$S_3 : r_j^k(t) \leq R_3 \text{ for } t > t_s, \quad (4)$$

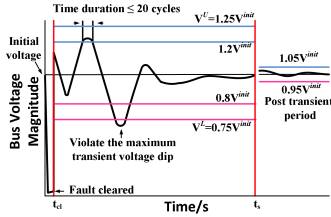


Fig. 2. Post-fault voltage performance criteria for a load bus.

where t_{cl} is the fault clearing time, t_s is the post-transient time, and $T_{r_j^k}(t) \geq R_2$ is the time duration for $r_j^k(t) \geq R_2$. Typical parameters are $R_1 = 25\%$ for load buses and 30% for generator buses, $R_2 = 20\%$, $D = 1/3$ second, $R_3 = 5\%$, and $t_s = 3$ second [35]. For a load bus, the post-fault voltage trajectory and criteria S_1 – S_3 are illustrated in Fig. 2.

To effectively and economically mitigate FIDVR, it needs to determine the optimal placement and sizing of dynamic var sources such as static var compensators (SVCs) and static synchronous compensators (STATCOMs) as well the incorporation of volt/var support from DER. Placement and sizing are usually solved separately, but can also be solved simultaneously as a sequence of mixed integer programming problems [36]. For placement, the key is to determine which candidate locations can best improve FIDVR prevention and post-fault voltage recovery. It is challenging mainly because 1) the input-state behavior can be highly nonlinear and complicated, 2) the post-fault trajectory requires solving differential-algebraic equations, 3) the placement depends on the selection of contingencies, and 4) the computational burden increases as the number of var sources grows. DER could potentially prevent FIDVR by not allowing the voltage during remote fault conditions to deepen low enough to cause air conditioner compressors to stall. The post-fault voltage recovery can be achieved by calculating a voltage sensitivity index for selected contingencies [37], [38] or by using the empirical controllability covariance that can consider the nonlinear dynamics and reduce the dependency on the selection of contingencies [39].

The optimal sizing problem is very challenging because 1) it is a non-linear, non-convex optimization problem due to the geometric characteristics of its solution space [4], 2) checking the constraints requires the post-fault voltage trajectories that can only be obtained by solving a power system differential-algebraic equation model [39]. It is usually formulated as a mixed integer programming problem and addressed by interfacing a heuristic optimization algorithm with power system simulation. For large systems, the computational complexity is high and the solution can easily converge to local optima.

The optimization problem is solved by interfacing branch-and-bound and multi-start scatter algorithms [40] or a Matlab-based toolbox KNITRO [41] with power system time domain simulation. Other approaches include multi-objective evolutionary algorithm MOEA/D [42], heuristic optimization [43], particle swarm optimization [44], heuristic linear programming [45], and Voronoi diagram [46]. In [4], the geometric characteristics of the solution space is investigated and the Voronoi diagram method is integrated with linear programming. Ad-

ressing the high computational complexity and solving the optimization problem by exploring the unique features of the problem are still an important research direction.

C. Thévenin Equivalent for Voltage Stability Analysis

One method to analyze the voltage stability of a load center is to model its power supply with a fixed impedance to a voltage source, which can be presented by a Thévenin equivalent. It can be easily obtained from simulation by increasing load. From impedance matching principle, the maximum power delivery occurs when the load impedance magnitude equals the Thévenin equivalent impedance, based on which voltage stability margin can be readily computed.

Thévenin equivalent computation becomes difficult when using measured data. The challenges include measurement noise, small load variations, and generator excitation system voltage adjustment as loads vary (the last leading to a variable Thévenin voltage as a function of time). A survey of methods, mostly based on PMU data, for long-term voltage instability detection was given in [5]. There are several documented schemes in computing Thévenin equivalent from data.

- 1) Measured data is fitted to the active power-voltage curve (PV curve) of the Thévenin equivalent by the least mean squares method [47], [48]. This method is suitable for PMU data obtained from disturbances.
- 2) In [49] a real-time algorithm estimates the Thévenin equivalent seen from a given bus through local PMU data, providing high-speed increase/decrease (due to perceptible system load variations) of Thévenin equivalent parameters, until reaching their new values. This allows a fast and continuous tracking of the evolving Thévenin parameters when voltage instability is approaching.
- 3) The Thévenin reactance is estimated, from which the Thévenin voltage can be computed. This method can be applied off-line to get a general trend of the Thévenin equivalent, and on-line to track the variation of the Thévenin equivalent in a finer time scale. This method has been applied to a wind hub in a 230-kV system [50].

All three methods are applicable to both on-line and off-line estimation. In off-line estimation, longer data windows are used. The calculation methods remain the same.

For future research, one major challenge is how to properly verify and validate these measurement-based methods by extensive testing using measured SCADA and PMU data from power systems. In addition, another challenge is to develop methods to effectively extract Thévenin equivalent voltage and impedance for measured data in ambient conditions that only show small variations in power and voltage magnitude.

III. VOLTAGE CONTROL IN ACTIVE DISTRIBUTION GRID

The interconnection of high penetration levels of DER will change the distribution grid's loading patterns, influencing the performance of voltage regulation devices. The difficulties in coordinating voltage regulation devices under high distributed generation (DG) penetration are driving utilities to have more stringent grid connection requirements. For instance, in Germany the EN50160 standard dictates that the voltage should remain within $\pm 10\%$ of the 10-min average of the RMS value [51], [52]. At the medium voltage (MV) level, and for

the units rated between 3.68 kVA and 13.8 kVA at the Low Voltage (LV) level, the DG units should be able to vary their power factor from 0.95 (leading) to 0.95 (lagging). In addition, for units rated above 13.8 kVA the power factor should be controllable from 0.90 (leading) to 0.90 (lagging).

In U.S., DG units may regulate active and reactive power with coordination between the system operator and DG operator based on IEEE 1547 [53], [54]. Actually active power adjustments are being mandated to support voltage regulation in IEEE 1547-2018 [54]. The voltage regulation standard is based on the ANSI C84.1-2016 standard's Range A definition [55]. The voltage should be maintained within $\pm 5\%$ for LV side, and for MV side the upper and lower limits are, respectively, $+5\%$ and -2.5% . Hawaiian electric is proposing voltage criteria of $\pm 2.5\%$ for day-time and $+5\%/-2.5\%$ for evening for MV networks to accommodate future DG growth [56]. In Ontario, Canada, for DG units rated over 30 kVA the power factor has to be controllable between 0.95 (leading) to 0.95 (lagging) and the Hydro one LV voltage should be within $\pm 6\%$ [57]. The participation of DER on voltage control depends on their reactive power capability and active power modulation. Accordingly, the system behavior in response to small or large disturbances may be different for various DER technologies.

Further in this section, the major voltage challenges associated with high DER penetration are discussed in Section III-A. Section III-B categorizes and summarizes various type of voltage control methods for DG units and Electric Vehicles (EVs). Whereas, Section III-C summarizes the voltage control techniques for microgrids. Going further, Section III-D discusses the challenges of real-time smart inverter based volt/var control (VVC) recommended by the integration standard IEEE1547-2018. To address challenges of smart inverter, the new type of VVC devices are discussed in Section III-E.

A. Voltage Issues Due to High DER Penetration

High DG penetration and integration of EVs lead to the following issues in distribution systems.

1) *Voltage rise*: A known issue from DSOs is voltage rise when PV production is high, particularly at the far end of the LV feeders [58], [59], which can lead to conservative limits on PV installation. The high R/X ratio in LV systems makes the voltage magnitude more sensitive to the active power injection than to reactive power. This is exactly opposite to the high voltage grids for which the R/X ratio is low and the grid operator uses reactive power to regulate voltage.

In Fig. 3, PV is injecting power to the system through a series impedance representing the electric distance between the PV plant and the Thévenin voltage of the grid. This impedance is certainly not constant in reality, depending on the power flow, grid configuration, etc. The analysis here serves as a qualitatively illustration of the voltage characteristics in different grids, and is applicable for all DG units. Assume the receiving end voltage \dot{V}_T is at the standard position (voltage angle is zero), the expression of the voltage drop across the series impedance is:

$$\Delta \dot{V} = \left(\frac{P + jQ}{V_T} \right)^* (R + jX) = \frac{PR + QX}{V_T} + j \frac{PX - QR}{V_T}. \quad (5)$$

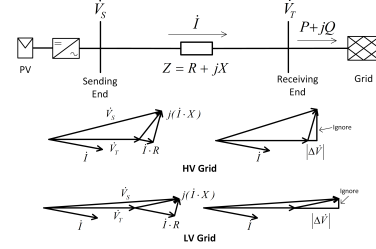


Fig. 3. The principle of voltage characteristics.

In systems with low R/X ratios, the voltage drop can be expressed by ignoring the resistance effect:

$$\Delta \dot{V} = \frac{QX}{V_T} + j \frac{PX}{V_T}, \quad (6)$$

where the magnitude drop $|\Delta \dot{V}|$ can be approximated by ignoring the imaginary component. In high R/X ratio systems, the effect of resistance is significant. Instead, the magnitude drop $|\Delta \dot{V}|$ in LV system may be approximated by

$$|\Delta \dot{V}| = \frac{PR + QX}{V_T}. \quad (7)$$

Suppose the voltage at the substation is constant, an increment of active power transmission from PV to the substation will increase the sending end voltage. By applying negative reactive power increment, this voltage magnitude difference may be reduced. To regulate voltage, the PV plant can reduce active power injection or apply negative reactive power injection as required by the IEEE 1547-2018 [54]. If reactive power cannot sufficiently regulate voltage, active power control could be implemented with controllable loads such as heat pumps, EVs, or battery storage. For example, the EV charging points that coordinate with small DG units to control voltage [60], [61]. In [62] a voltage unbalance mitigation strategy is proposed by coordinating PV inverters and demand side management.

2) *Voltage drop*: This is a classical voltage problem dealt with by DSO. The adoption of EVs will add more challenges, particularly overloads and excessive voltage drops at peak load. These problems will aggravate if vehicle owners have no incentive or information to schedule battery charging for optimized grid utilization [63]. It is required to control their charging rate and time of connections with a fair distribution of efforts among EVs. Moreover, the way charging points will be controlled with limited communication is still searched for.

3) *Impact from reversed power flow*: Distribution systems are designed to operate for unidirectional power flow. Existing line voltage regulators (LVRs) usually correct voltage drop on the load side. Voltage is sensed at the load-side of the LVR and taps are adjusted to correct the load-side voltage. When DER is back-feeding a voltage regulator, the regulator will change taps to correct voltage. In addition to the feeding main grid, as local current sources DER can also control the local voltage by manipulating their currents. If LVR operates in constant-voltage mode, it will decrease load-side voltage if DER increases it. However, the voltage of DER connection point may still be too high if the number of taps is not adequate or the LVR set-point is determined assuming unidirectional

power flow and there is distance between LVR and DER. If LVR operates in line-drop-compensation mode, DER can cause significant problems since it will increase the voltage at its secondary-side under reverse flow. This will worsen the situation if there is already voltage rise caused by DER. Even if LVRs are bi-directional, they can only control local voltage. When there is voltage rise due to reversed flow, only the DER and/or voltage regulation devices installed at the DER vicinity can provide full voltage correction between DER and LVR.

4) *Voltage fluctuation*: Higher voltage fluctuation due to cloud cover variations can lead to poor power quality and high voltage variability across the entire feeder. Further, in the presence of smart inverters, in order to ensure system stability, the volt-var curves are chosen to have higher deadbands ($\pm 3\%$) and larger slope ($\pm 3\%$) [64]. These factors lead to reduced upper and lower voltage margins in reference to the ANSI-A limit (114 V–126 V) for performing conservation voltage reduction (CVR) and Volt-Var control (VVC) functions [65].

B. Local, Decentralized, Distributed, and Centralized Control

Voltage control techniques in the active distribution grid can be classified into four categories: *local control*, *decentralized control*, *distributed control*, and *centralized control* [6]. Proper selection and trade-off of different control architectures is one major challenge for voltage control.

1) *Local voltage control*: The control decisions of the DER are made based on local voltage/current measurements at the point-of-interconnection. Voltage control is provided through reactive power control of dispersed DG units, active power curtailment of DG generation, and smart charging of EVs, which can reduce the impact of renewable generation and minimize the need of auxiliary equipment for voltage control [66]–[68]. Although local control techniques do not require communication [69], its inability to align with the utilities' control strategy is the main drawback.

For a simple 2-bus system, the reactive power required to maintain constant voltage for a given increase in active power ΔP can be approximated as $Q = -\Delta P \cdot R/X$, where R and X are the resistance and reactance of the branch [70]. One problem is that in MV and LV branches the R/X ratio tends to be high [71] which results in higher reactive power requirement. This leads to high power rating requirements of inverters and can also increase the losses in the circuit. Active power curtailment (APC) is another viable method to prevent overvoltage [70], in which the output power of inverters that are typically operated at their maximum power point is curtailed. Adaptive techniques such as online adjustment of droop values for APC have been proposed [72], [73]. Other methods incorporate Energy Storage Systems (ESSs) [74] and use a mixture of reactive and active power control strategies [75]. Specific challenges related to real-time local smart inverter control will be discussed in detail later in Section III-D.

2) *Decentralized voltage control*: It aims at enhancing local control using low-form communication system [76]. This may include coordination among various system components in an automated manner without regulation from the system operator (although some strategies may optionally communicate with the system operator) to optimize local grid operation [66], [77]. A global distress signal is used under overvoltage conditions

in [78]. The controller is implemented as a finite-state machine and prioritizes reactive power support over active power curtailment. In [79], a decentralized robust energy management method for distribution networks with renewable DG units is developed based on the alternating direction method of multipliers (ADMM) algorithm.

A multi-agent market based control of EV charging that considers transformer and voltage limitations is presented in [80]. The EV agents communicate simple messages to substation agents. The EVs are charged at minimum cost, without affecting the network and keeping the customer welfare at maximum at all times. Compared with centralized schemes, decentralized schemes can provide flexible, efficient, and robust regulation for smart distribution networks [9].

3) *Distributed voltage control*: This is a voltage control scheme without a central controller, and implemented with node-local computations using only local measurements augmented with limited information from the neighboring nodes through communication channels [9]. In [81], a two-stage distributed voltage control scheme is proposed. The first stage is the local control of each DG based on sensitivity analysis and the second stage acquires reactive power support from other DG units. In [61], a consensus-based cooperative control is proposed to regulate voltage by coordinating EVs and active power curtailment of PV. In [82], a distributed voltage stability assessment considering DG units is developed based on distributed continuation power flow.

4) *Centralized voltage control*: Also known as active network management, it utilizes sophisticated communication networks to regulate voltage [83], [84]. State estimation is used to estimate voltage profile, based on which DG and other components are dispatched [85]. Through a coordinated control of on-load tap changer (OLTC), DG, and voltage regulators, a centralized control approach allows optimized operation of the entire region of the grid under the system operator [86], [87]. In [88] a primary cabin (PC) voltage control is proposed for distribution grids, which is a hierarchical control with decentralized functionalities at the PC level and centralized functions in the distribution management system (DMS) for coordination among PC controls. Centralized controllers have also been explored for voltage drop mitigation due to EV charging, including optimization [89], [90] and rule-based options [91]. Centralized control can have better performance than decentralized control due to the optimization of the resources. However, it requires a reliable communication network using protocols such as DNP 3.0 or IEC 61850 with considerable investment in sensors and measurements.

C. Voltage Control in Microgrids

Microgrids are subsystems of loads, DER, and ESSs with clearly defined electrical boundaries that can act as a controllable entity. They can disconnect from/connect to grid at the point of common coupling (PCC) to operate in islanded/grid-connected modes. Some countries still apply DG interconnection requirements for microgrids based on IEEE 1547.4 [57].

The microgrid controller is responsible for coordinating DER and loads to achieve desired P/Q or volt/var at PCC. Centralized approaches require a fast, reliable communication

between DER and the microgrid controller. Controllers utilizing local information may not be suitable for all operating conditions [92]. Distributed approaches relying on limited communication have thus been proposed. Under this context, a hierarchical approach consisting of primary, secondary, and tertiary control is typically employed for voltage control of microgrids [93]. The primary controller is usually a droop-based controller which regulates the voltage through reactive power sharing. The secondary and tertiary controllers are responsible for any steady-state errors [94].

In a weak grid, voltage stability can also be a concern [95]. For example, the operation of microgrids with synchronous machine based DER under unbalanced condition may result in stability issues [96]. If voltage unbalance is not properly compensated by system controls, high power oscillations may appear at double frequency due to negative sequence components, resulting in disconnection [97]. Techniques such as injection of negative sequence components [98] or voltage stabilizers [96] have thus been proposed.

On the other hand, the voltage control in islanded microgrid with high renewable penetration is also challenging. In islanded microgrids, the task of voltage control is attributed to the master controller of the system. Since the R/X ratio in microgrids is high, the frequency and voltage control cannot be fully decoupled. Significant, sudden change in renewable generation may lead to voltage and frequency instability, if the voltage and frequency are not properly controlled by grid-forming DER and the microgrid controller.

The work in [99] presents a technique for controlling a system of inverters in islanded low-inertia microgrids. The AC output of each inverter is modulated to emulate the dynamics of a nonlinear oscillator. The local controllers only require local measurements available at the AC terminals. The inverters adjust their power output to match the load while maximizing energy delivery and keeping the steady-state voltages within limits for all loading conditions.

D. Challenges of Smart Inverter Volt/Var Control (VVC)

The focus of this section is to discuss the challenges of real-time smart inverter VVC in the context of integration standards such as IEEE 1547 [54]. The earlier version of IEEE 1547 [53] and Rule 21 in California [64] preferred DER to operate in unity power factor mode to avoid unexpected issues. However, their revised versions such as IEEE 1547-2018 include the functionality of local regulation of voltages through inverter VVC [54]. A typical VVC scheme recommended by these standards known as ‘droop’ VVC is a piecewise linear curve with negative slope. The droop curve allows var injection/absorption for low/high voltages [100]. Due to its simple design and easy implementation, it has been explored by [101]–[104] and recommended by integration standards.

There are several challenges for the droop VVC framework. First major issue is of its vulnerability to control instability due to inappropriate control parameter selection. It has been reported by several studies that the smart inverter parameters need to be determined appropriately based on the feeder configuration and operating conditions such as load profile, solar penetration level, desired voltage set-point, cloud cover

etc.; and a slight variation in the settings can yield significantly different responses [105]–[107]. Specifically, VVC is highly sensitive to its droop (slope) parameter and an improper slope selection may lead to control instability or voltage oscillations (voltage flicker) [101], [102], [104]. Another issue with droop VVC is that due to its inherent proportional control design, there is always a compromise between maintaining control stability and achieving set-point tracking accuracy which can potentially lead to voltage violations as shown in [104]. Another major issue is the non-adaptability of the droop VVC in changing conditions which challenges the real-time implementation of the control.

The recent literature has recognized and attempted to address these issues. For instance, delayed VVC [102] improves the control stability but does not discuss the parameter selection and set-point tracking accuracy. A scaled VVC [103] addresses both control stability and set-point tracking. However, it is not compatible with standard droop VVC framework and also requires full centralized topology information. An adaptive droop VVC [104] addresses these issues by making parameter selection self-adaptive to changing operating conditions and external disturbances such as a change in substation voltage, sudden cloud cover, cloud intermittency and sudden load changes. However, this problem of VVC becomes even more complex in a real-world due to thousands of inverter devices operating simultaneously. Addressing these challenges will enable the smart inverters to be utilized to their fullest potential for enhancing the distribution system performance under a wide range of operating conditions.

E. Voltage Control by Low Voltage Var Controllers (LV VCs)

Smart inverters may inject/absorb vars or inject/curtail watts locally to deal with undervoltage/overvoltage issues. However, inverters are consumer owned assets and utilities do not control where the next smart inverter is installed on the grid [108]. Future controllability of smart inverters would require utilities to integrate them into their SCADA, DMS, or DERMS, either directly or via a system aggregator, which can be challenging. To address these challenges, LV VCs have been developed, which use power electronics-based, fast-acting, decentralized shunt-var technology for voltage regulation. Each device is connected to the secondary-side of a pole- or pad-mounted service transformer to tightly regulate the voltage ($\pm 0.5\%$ within a set-point) at local and feeder-wide by injecting or consuming 0 to 10 kvar [109]. When the voltage goes below the set-point, the LV VC will inject incremental capacitive vars to boost the voltage; when the voltage goes higher than the set-point it will remove the incremental capacitive vars to reduce the voltage, thus tightly regulating the local voltage. Further, a cluster of LV VCs have a voltage tightening effect even on the primary MV side which can help regulate the voltage where there are no LV VCs [110]. As utility owned assets, they can not only manage the PV-induced voltage fluctuations and overvoltage issues but can also provide incremental benefits of performing CVR for demand management and energy savings.

LV VCs has been deployed at the 12.47-kV Keolu substation of Hawaiian Electric on the island of O’ahu where there is over 90% of PV penetration (4.3 MW residential PV) [111].

Sixty-one LV VC devices were deployed on two circuits to tighten the voltage by almost 50%, which allowed lowering LTC voltage from 122 V to 119.5 V to create an upper voltage headroom (see Fig. 4). The studies have shown that LV VCs could allow Hawaiian electric to increase PV penetration from 90% to 125% without causing any curtailment.

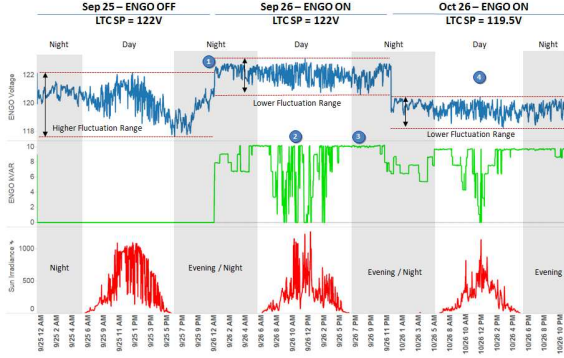


Fig. 4. Top plot: Secondary side voltage; Middle plot: Vars injected by SVC; Bottom plot: Solar Irradiance. Plot is divided into three parts: i) Left most part shows a day when LV VCs are OFF; ii) Middle part shows a day with LV VCs turned ON; iii) Right part shows a day with LTC set-point lowered and LV VCs turned ON with a lower set-point.

IV. COORDINATED VOLTAGE CONTROL CONSIDERING INTERACTIONS OF TSO AND DSO

A. Motivation of TSO and DSO Coordination

About ten years ago, industry and academia noticed the necessity of coordinating TSO and DSO for voltage control. The initial motivation, as demonstrated in the Swiss grid project [112], was to limit reactive power exchange at the transmission-distribution interface when there are scarce reactive power resources in a TN. Then, with DER increasingly integrated, people recognized that a DN with DER has flexibility in adjusting its reactive power consumption to provide reactive power reserves and improve TN voltages [113]–[116]. Due to their geographically distributed nature, if the DER are properly coordinated, they may provide more flexible and localized var support to the bulk system at lower cost than installing var devices in TN [116]. Positive effect of the coordination was verified on a Danish power system [117], and the ENTSO-E network code now stipulates that a TSO must retrieve the reactive power reserves of each DSO [118]. Meanwhile, under high DG penetration the reverse power flow caused by DG units unwantably increases TN voltages and even saturates OLTCs at boundary buses, which leads to the voltages of TN and DN being no longer uncoupled [119]. In this case, TSO and DSO must coordinate to control voltages.

TSO in Great Britain has detected a declining trend of reactive power demand under light load due to less inductive loads and higher DG penetration [120]. Hence, tap staggering in parallel step-down transformers is proposed to reduce reactive power surplus in TNs [121]. Here, an intentional offset in transformer tap positions induces a circulating current that results in reactive power absorption. This is extended in [122] to calculate the optimal transformer tap positions that minimize losses and the number of switching operations.

B. Rule-Based Methods vs Distributed Optimization

As for coordination methods, both rule-based methods and distributed optimization have been studied. Early work is exemplified in [123]–[125], where an allowable range of the boundary-bus reactive power is sent from DSO to TSO who then determines the boundary-bus reactive power and voltage setpoints. Furthermore, [119] suggested an MPC to be implemented by the DSO in a finer-grained resolution to ensure suitable distribution system voltages while the DSO optimally tracks the boundary-bus reactive power setpoint from TSO. In [126] an MPC-based controller keeps DN voltages within limits by coordinating DG and classical control devices and ensures that the power factor at DN’s connection point or the reactive power exchanged with TN remains within limits.

However, these methods may deteriorate the optimality of a DSO’s voltage control target. To resolve this issue, TSO and DSO can repeatedly solve their local voltage control problems and exchange boundary-bus voltage and power until there is feasible power flow [127]. Alternatively, [128] and [129] propose a curve fitting approach to represent the “response” of the optimal value of a DSO’s problem regarding possible boundary-bus voltage set-points and incorporate this information into a TSO’s problem to produce a boundary-bus voltage set-point. Hence, the iterations between TSO and DSO required in [127] are avoided. To ensure that the voltage setpoint given by TSO always leads to feasible DSO operation, a feasibility constraint is included in the TSO’s problem [129].

Rule-based methods may not converge, or the converged solution may not be optimal. Distributed optimization theory is thus applied for an effective coordination. The well-known decentralized and iterative algorithms, e.g. APP [130], ADMM [131], AND [132] or OCD [133], are applied, and the generalized Benders decomposition algorithm is also tested in [134], in which a global reactive power optimization model is proposed for transmission and distribution grids. In contrast to those algorithms originally designed for general purposes, the heterogeneous decomposition (HGD) algorithm in [135] seizes the heterogeneous TSO-DSO operation features where a TSO oversees the boundary-bus voltage and a DSO supervises the boundary-bus power. It suggests that the boundary-bus voltage and power should be determined respectively by TSO and DSO and then be exchanged between them. [135] further analyzes the differences between HGD, APP and OCD algorithms and tested their performance on TSO-DSO coordination. Although these algorithms are more rigorous than heuristic methods, more field tests are needed to validate their robustness against complicated operational conditions.

In [136], a model-free optimal dispatch of controllable DER is proposed to control the power exchange between TN and DN while maintaining DN bus voltages within limits. It is based on a two-dimensional extremum seeking (ES) control that adds orthogonal sinusoidal perturbations to active and reactive power of controllable DER. It avoids any network model but relies on synchronized measurements of both the DER power output and the measured objective function.

C. DN Supporting TN in Emergency Conditions

As in Section III, many control schemes are proposed to regulate DN voltages. However, most of them rely on a strong (stiff) TN which may not be the case as large disturbances, such as line tripping or generation outages, weaken the TN.

DNs can help TNs by providing fast reactive power injections from multiple DG units. DNs can also reduce their demands by increasing local generation of active (if any) and reactive power, or coordinate DER to avoid the power recovery of voltage sensitive loads after a dramatic TN voltage drop. Restoration of these loads is slow due to OLTC actions and may lead to long-term voltage instability conditions [137].

DN voltage control schemes that ignore the conditions of TNs may precipitate long-term voltage instability due to fast load power recovery activated by fast response of the DG units restoring DN voltages [138]. Additionally, local identification of emergency conditions [139], based on monitoring the unsuccessful attempt of OLTCs to restore DN voltages, could become more difficult, as DG units may temporarily bring DN voltages back to or close to pre-disturbance conditions, hiding the problem faced by the TN. To avoid these problems, an emergency signal from the TN could be used to temporarily change the DN voltage controller's logic in order to positively help the TN to reach a new long-term equilibrium point.

DN voltage control that provides support to TN could also benefit from demand response strategies, as direct control of thermostatically controlled loads (TCLs), EVs and ESSs could temporarily reduce the active/reactive power demands of DNs. The coordination, communication requirements, and how DER participates in voltage control need to be carefully investigated.

D. Transmission-Distribution (T-D) Co-Simulation

In order to utilize DER's Volt/Var capability to enhance TN performance, a proper coordination between TSO and DSO is needed. An optimization framework is required which provides ancillary services to TN while maintaining DN voltages within the operating limits. In one such attempt, [140] proposes a real-time algorithmic framework which meets the real power demand request from TSO at the feeder substation by controlling DER output. DN voltage limits are enforced via constraints in the optimization. Similarly, [141] minimizes the reactive power demand at the feeder substation using fixed power factor mode of DER. However, all such studies represent the TN as a substation and therefore it is impossible to observe the direct impact of this coordinated control on the grid.

In order to investigate the true impact of DER var support on transmission performance, T-D co-simulation is required [142]. [143] discusses how co-simulation provides more accurate long-term voltage stability assessment with DER penetration compared to only TN or DN simulation. In conventional TN simulation, the load is aggregated at substation and the full DN topology is not modeled. In conventional DN simulation, the substation voltage is assumed fixed, thus TN's impact on substation is neglected. There have been some recent attempts to develop T-D co-simulation methods and platforms [144]–[146] but there is still a large scope of customizing utilizing these platforms for the concerned DER Volt/Var application.

E. Future Directions for TSO and DSO Coordination

The study in [138] shows that a DSO's voltage control affects the static instability of an integrated system. It is thus necessary to take this factor into account when designing a coordination method. However, the conventional TN or DN voltage stability assessment is inaccurate in predicting the long-term (or "static") voltage stability margin of an integrated system, as shown in [142], [143]. A distributed algorithm is proposed in [82] to accurately evaluate the static voltage stability of an integrated system, which conforms to the distributed architecture of coordinated voltage control methods.

Although many distributed coordination methods have been proposed, they need to be further tested. Also, most work does not consider electricity market when designing coordinated voltage control. Since in some systems only a few voltage regulation devices are owned by TSOs, the price mechanisms of dispatching var resources should be considered.

V. CONCLUSION

In this paper we perform a thorough review on the emerging challenges and opportunities of voltage control in transmission grid, distribution grid, and on coordinating the TSO and DSO. For TN, voltage fluctuation, cascading trip, and FIDVR are the major challenges. For DN, advanced control strategies are needed to mitigate the impact of DER integration. As for TSO-DSO coordination, stability and market should be considered.

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