Distribution Voltage Control: Current Status and Future Trends

Jin Dong*, Yaosuo Xue†, Mohammed Olama‡, Teja Kuruganti‡,
James Nutaro‡ and Christopher Winstead‡
* Energy and Transportation Science Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
dongj@ornl.gov
† Electrical and Electronics Systems Research Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
xuey@ornl.gov
‡ Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
{olamahussemm, kurugantipv, nutarojj, winsteadcj}@ornl.gov

***Abstract*—Driven by smart distribution technologies, the widespread use of distributed energy resources (DERs), and the injection of new loads, such as electric vehicles, electric distribution systems are evolving from passive to active. The integration of DERs (including renewable distributed generation) with their uncontrollable generation variability, imposes various grid stability challenges on distribution system operation. The primary problem is significant voltage rise in the distribution feeder that forces existing voltage control devices such as on-load tap-changers and line voltage regulators to operate more frequently. The consequence is the deterioration of the operating life of the voltage control mechanism. As such, a distributed active network management has to be fulfilled by taking advantage of the emerging techniques of control, monitoring, protection, and communication to assist distribution network operators in an optimal manner. This paper presents a short review of recent advancements and identifies emerging technologies and future development trends to support active management of distribution networks.**

I. Introduction

The uptake of distributed energy resources (DERs) has imposed significant challenges on the distribution system operatiopn. Particularly, the uncertain and intermittent nature of renewable resources (especially photovoltaics (PV) generation) will not only create voltage rise and violation of node voltage limits, but also the life of the distribution transformer will be reduced due to rapid and continuous tap changing adjustments. The consequence is the deterioration in both performance and operating life of the existing voltage control mechanism. Also, conventional non-coordinated reactive power control can result in the operation of the line regulator at its control limit (runaway condition) [1].

Distribution voltage control is usually associated with three objectives, power quality, energy efficiency (i.e. reducing power loss and/or peak load), and voltage stability, also known as voltage instability or collapse. In this work, we also add the fourth-dimension objective, extending the lifetime of voltage regulation devices, e.g. step voltage regulators and distribution transformers with on-load tap changers. Next-generation distribution systems should be efficient and optimized system wide, highly reliable and robust, and capable of effectively managing highly penetrated DERs, electric vehicles (EVs) and other controllable loads [2]. To meet these new challenges, various distribution management technologies, such as distribution automation, automated reconfiguration, and VAR control, have been investigated [3], [4]. There still exists a knowledge gap for voltage impact analyses before advancing to address grid integration challenges of increasing solar PV penetration. Our previous papers [5], [6] have analyzed transmission system performance with high PV penetration on both IEEE 13-bus system and real-world distribution circuit.

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy.

In this paper, we will depart from reviewing various control architectures for the distribution nodal voltage control to assure power quality to the end consumers. The term power quality refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system. Among those disturbances, the nodal voltage controls mainly target on preventing under-voltages and over-voltages by voltage regulation at fundamental frequency [7]. For harmonic-related power quality issues, various passive or active power filters (APF) can be installed to compensate voltage harmonic distortions due to nonlinear loads nearby. Within the APF family, the concept of Unified Power Quality Conditioner (UPQC), which integrates both shunt compensation and series compensation in one system, is referred to in power distribution systems, while the Unified Power Flow Controller (UPFC) is employed in power transmission systems. Here we will not extend our discussion on the details of UPQC. However a comprehensive overview of different UPQC power electronics converter topologies and system configurations can be found in [8] and [9]. Then we will discuss the emerging control technologies that enable the aforementioned novel management methods and strategies.

II. Distribution System Architectures

Electric distribution systems refer to the portions of medium-voltage and low-voltage electric power grids. In North

America, standard medium voltages range from 600 V to 69 kV, and low voltages are any voltage below 600 V. Typically, residential houses are connected to low voltage lines, 120 V single phase or 240 V split phase; commercial buildings are connected to three-phase 480 V or 690 V. These low voltage loads are called secondary customers from the utility perspective. The lower end of medium-voltage distribution grid serves the primary customers at 4.16 kV to 13.8 kV, and the higher end of medium-voltage distribution grid serves sub-transmission customers at 26 kV to 69 kV.

Different distribution system architectures are adopted in different areas and different countries. The choice of distribution architectures has connotations of cost and reliability concerns [10]. In general, the sub-transmission and primary distribution systems can be designed in looped, radial, meshed (also called interconnected or spot network), or T-type structure. In the United States, two major distribution system architectures are commonly used [11]. The radial distribution structure is typically used in the rural areas, while the meshed network structure is more deployed in the densely populated city areas.

A. Radial Network

The radial distribution feeder circuit, with one example shown in Fig. 1, traditionally has only one single source from the distribution substation and no switch device linking that circuit with another, hence suffering from reliability concerns if a fault occurs close to the substation and power quality issues at the feeder end due to the voltage drop or power loss of the long feeder line. This structure has a historic root, but remains the majority in the country.

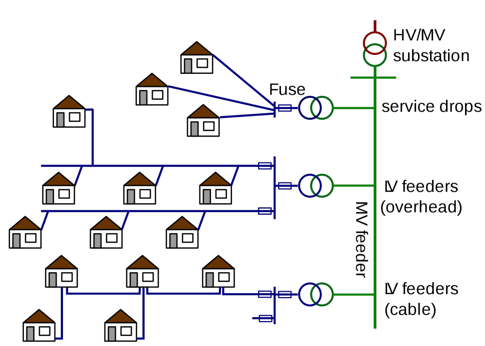

Fig. 1: A typical radial grid network distribution system [12].

B. Mesh Grid Network

In high load city areas, meshed secondary networks [13], as shown in Fig. 2, are installed, which consists of multiple distribution voltage-level feeders, each serving several underground transformers installed in vaults, with the low-voltage secondaries of the transformers interconnected, and customers served from these interconnected secondaries. This type of architecture provides a very high degree of reliability to the service provided to the customers, as a number of components can be out of service at any one time. However, higher construction cost has limited its expansion.

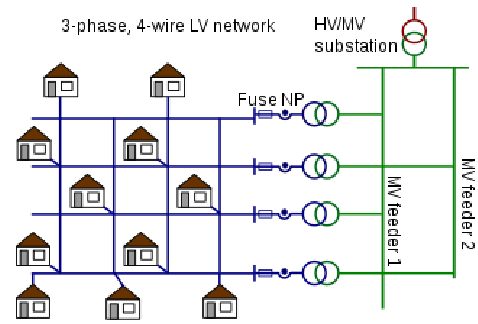

Fig. 2: A typical mesh grid network distribution system [12].

Recent extreme natural events, such as Hurricane Maria and Superstorm Sandy, have called for grid resilience, which requires distribution system capable of fast restoration and self-healing. The technology advances of distributed intelligence and distribution automation [4] serves for this purpose, which can change the radial distribution structure dynamically to improve reliability and resilience utilizing devices like sectionalizer, recloser, power flow controller, and fault location/isolation/service restoration (FLISR) or fault detection/isolation/restoration (FDIR).

III. Distribution Voltage Control Problem and Control Structures

Distribution utilities are obliged to guarantee power quality to customers. The term power quality is associated with the electromagnetic phenomena, such as 1) transients, 2) short duration variations, 3) long duration variations, 4) voltage unbalance, 5) waveform distortion, 6) voltage fluctuations, and 7) power frequency variations. The voltage control devices are primarily deployed to handle type 3 disturbances, in particular, preventing under voltage and overvoltage, by voltage regulation at fundamental frequency. This problem is also referred to as the nodal voltage profile or maintaining viable voltage level, and mainly investigated below. Another type of voltage stability problem is voltage collapse, which investigates the overloading point (bifurcation) at which the voltage will collapse.

A. Conventional Control Architecture

To improve nodal voltage profiles in medium-voltage distribution networks, different voltage control devices are utilized by distribution utilities. The substation transformers are typically equipped with on-load tap changers (OLTC). Step voltage regulators (SVR) can be also installed in the middle of the feeder to boost the voltage by a transformer with LTC. Voltage drops can also be caused by the loads which absorb large reactive power, i.e. lagging power factor. Reactive power compensation devices, such as fixed or adjustable capacitor banks, and various power electronics based compensator, e.g.

staic var compensators (SVC), STATCOM, etc., are installed in the substation and along the feeders or close to particular loads. In low-voltage distribution networks, direct voltage control devices are seldom present traditionally.

In recent years, smart inverters and various grid edge technologies have evolved in the low-voltage distribution system to provide grid supporting ancillary functions. However, these new voltage control devices present impacts on the operation of conventional voltage control devices, and need to coordinate together to maintain proper voltage profile and reduce system loss.

The voltage regulation problem is traditionally approached in a hierarchical structure: offline optimization and online control, as shown in Fig. 3. The offline optimization problem defines the optimal settings for the online voltage control reference and the optimal sequences of connection and disconnection of the capacitors. This process is typically performed day-ahead based on 24-hours load forecasting. The online control problem targets at control of OLTC by closed-loop regulation to maintain the voltage amplitude at the reference value. The controlled voltage can be the transformer secondary voltage or the estimated voltage at the feeder end by the line drop compensator (LDC).

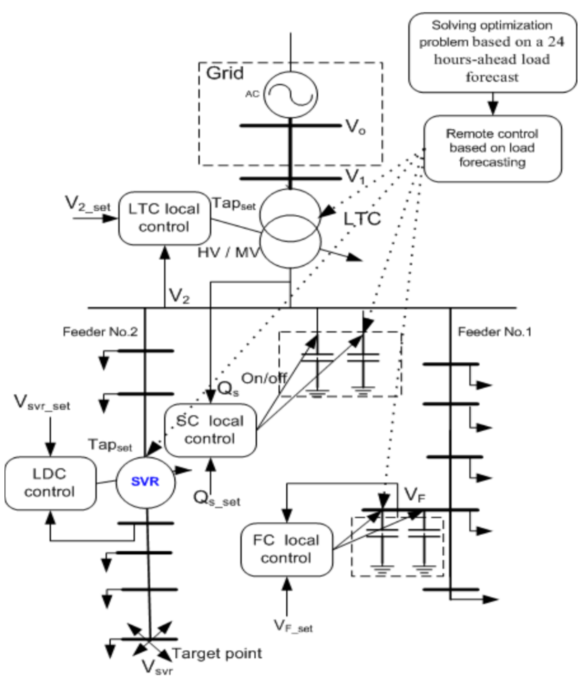

Fig. 3: Conventional voltage and reactive power control in distribution system [14].

While the LTC is placed on substation transformer and operates on three-phase basis, step voltage regulators (SVR) regulate individual phases, and can be placed flexibly at any feeder location where required, e.g. at feeder bus or head or in the middle of a long feeder line. A voltage regulator comprises of autotransformer, load tap changer, and voltage regulator control. A voltage change is obtained by changing taps of the series winding of the autotransformer. The position of the tap is determined by a line drop compensator. Standard step regulators contain a reversing switch enabling a $\pm 10\%$ regulator range for Type A SVRs and +10% and -8.3% for Type B SVRs, usually in 33 steps. This amounts to a 5/8% change per step, or 0.75 V change per step, on a 120 V base.

The step voltage regulator control circuit requires the following settings:

- Voltage Level: desired voltage to be held at the load center, typically between 114 V to 126 V.
- Voltage Bandwidth: the allowed variance of the load center voltage from the set voltage level.
- Time Delay: the length of time that a raise or lower operation is called for before the actual execution of the command. This setting is intentional to avoid unnecessary accelerated wear and tear of the tap changer for short duration of the voltage excursion outside of the bandwidth caused by the events of motor starting. It is typically set in the range of 30 to 90 seconds.
- Line Drop Compensator: set to compensate for the voltage drop between the regulator and the load center. The settings consist of R and X settings in volts corresponding to the equivalent impedance between the regulator and load center when the line is carrying the current transformers rated primary current.

B. Improved Control Architecture

Smart inverters can provide autonomous volt/var control or power factor control [15] to mitigate local voltage fluctuations and voltage rise issues due to solar power injection at the point of interconnection. However, market incentive mechanism has yet to be established for non-utility supplied reactive power. In addition, the provision of reactive power capabilities normally requires excess capacity on the inverter, and thus over-sizing hardware design or active power production curtailing. For smart inverters providing additional voltage support, communications and standardized control functions are required by the IEEE standards and specific grid codes, as to be reviewed in next section, to ensure that these functions are coordinated with distribution system regular voltage control operations and are enabled only when appropriated to do so [16]. Fig. 4 shows a control architecture and configuration [17] for the OLTC controller to consider the voltage at the feeder end by either estimate or remote monitoring.

C. Voltage/Var Optimization

The voltage control technologies in distribution systems are continually evolving. In both 1970s and early 2000s, with the energy and electricity crisis concerns, utilities looked at conservation voltage reduction (CVR) to increase distribution system efficiency and conserve energy. Over the years of technology improvement and communication establishment at most distribution equipment, the focus of minimizing energy consumption has shifted to controlling the voltage and volt-ampere-reactive power levels, i.e. VAR, in near real time. This is known to be referred as Voltage/Var Optimization (VVO)

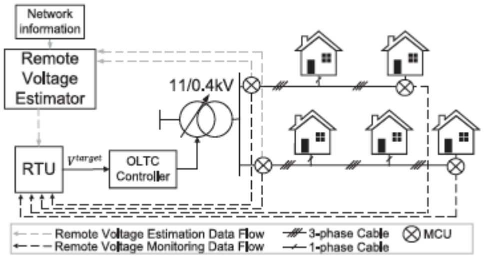

Fig. 4: Control architecture with and without remote monitoring [17]. (In the case without remote monitoring, the monitoring, metrology and communication units (MCUs) are installed only at the head of each feeder.)

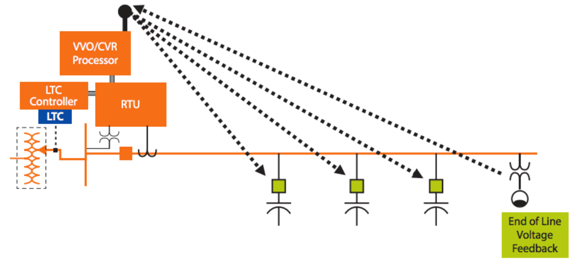

Fig. 5: SCADA rule-based VVO approach [21].

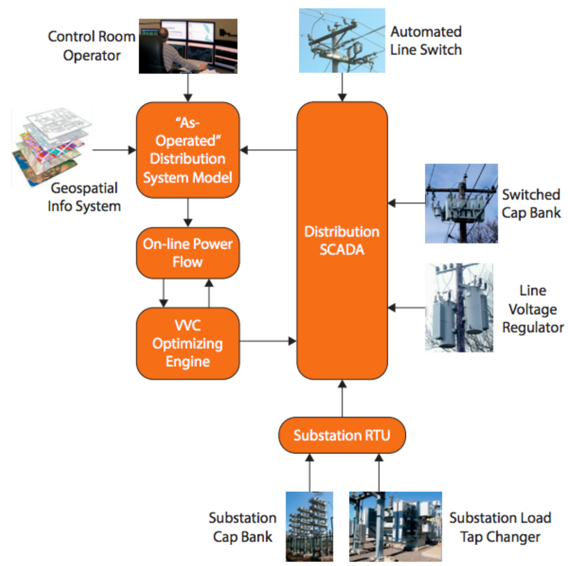

Fig. 6: DMS model-driven IVVC scheme [21].

nowadays. There exist different VVO control structures, centralized and decentralized.

Centralized VVO approaches use LTC transformers, voltage regulators, and fixed/switched capacitor banks to control voltage and reactive power flow. There are three different centralized VVO approaches [18], SCADA rule-based VVO, DMS model-driven VVO, and hybrid VVO. The rule-based system, shown in Fig. 5, uses a VVO processor in conjunction with a remote terminal unit (RTU) to control the automated devices. The design can incorporate the voltage of feeder end, and change the tap position or capacitor ON/OFF based on a set of rules and programmed voltage and VAR thresholds to achieve either minimized feeder losses, minimized energy consumption, minimized power demand, or any combination of these. The communications between the VVO processor and line devices can be via SCADA or cellular phone.

The model-driven VVO approach, as shown in Fig. 6, takes the advantage of the most information and tools available in a distribution management system (DMS), including near real-time network configuration, advanced metering infrastructure (AMI), outage management system (OMS), geographic information system (GIS), and customer information system (CIS), to develop and execute an optimal switching plan for all the controllable devices to reach a desired result. The core engine is the integrated volt-var controller (IVVC), which runs an online power flow analysis and optimization to create a VVO switching plan. The hybrid VVO approach emerges more recently utilizing auto-adaptive controllers in the field devices or at the system level to act and respond to changing conditions. These auto-adaptive controllers are based on either closed-loop control with real-time voltage measurement or historical behavioral patterns to optimize the power flow based on the rules provided by the utility. Decentralized or agent-based VVO schemes [19], [20] have attracted more and more attention to tackle the control scalability.

IV. Trends of Distribution Voltage Control

In this section, the emerging technologies that enable the aforementioned novel management methods and strategies are reviewed. The discussion is focused on the future development in the following selected areas: solar PV inverters, decentralized voltage control, coordinated voltage control, distributed STATCOM, and the concept of responsive building loads.

A. *Voltage Control by Solar PV Inverters*

Traditionally, electrical utility companies own the voltage regulation equipment, such as distribution transformers with on-load tap changers, step voltage regulators, and fixed or switching capacitor banks. which are installed only in the medium-voltage distribution grid. Centralized control schemes are typically adopted in practice by the utility. In recent years, with the emerging of residential PV (a few kilowatts), commercial building solar PV (a few hundred kilowatts), and utility-scale mega-watt solar farms, there is a demand to call for various grid services provided by solar PV inverters in addition to their primary energy feeding functions. Hence new voltage control devices are present in both medium-voltage distribution zone (typically MW-scale solar farm connected to 4.16 kV up to 69 kV grid) and low-voltage distribution zone (residential PV at single-phase 120 V/240 V and commercial building PV at three-phase 480 V). Usually the voltage control problem and reactive power control problem [22] are highly coupled with reactive power compensation to improve the load power factor and in the meantime to support the voltage.

B. Decentralized Voltage Control Philosophy and Operational Issues

With the emerging voltage control devices on the customer side and their distributed nature, naturally this has spiked up a lot of research interests towards decentralized voltage and reactive power control philosophy [14]. However, the operation impact of new voltage control devices needs to be studied first.

The effects of voltage control by the DER and the interactions between the DER and the utility voltage regulation devices (capacitor banks, voltage regulators and load tap changers) have been investigated in [1], [16], [23] on computer simulation bases.

Without proper coordination by distribution network planner and operator, the voltage control provided by the DER may introduce adverse effects including control interactions, operational conflicts, steady-state voltage variations, and oscillations. In [16], a sample medium-voltage distribution feeder system, shown in Fig. 7, is simulated and analyzed with two feeder circuit configurations and four case studies. It has been observed that more tap operations are required in step voltage regulators (VR) to correct the voltage according to their voltage reference value, since the distribution generation (DG) voltage control mode operation and associated voltage reference values of the DG units tend to damp the voltage correction by VRs, which could lead to unnecessary capacitor bank switching operations and exhausted tap operations. Also, the tap operations of voltage regulators do not significantly affect the remote end bus voltage, mainly due to the fast voltage control action of the inverter-based DG. In [16], the total number of conflicting operations in voltage regulators and capacitor banks have been reported, as replicated in Table I, based on one year 10-minute time resolution simulations. These simulation results highlight the DG and voltage regulating device interactions and their possible adverse effects under different system operational conditions.

TABLE I: Number of conflicting operations associated with DG voltage regulating device interactions, as found in [16].

Simulated Control States	No. of Conflicting Operations in VRs and CBs due to Simultaneous Responses	No. of Conflicting Operations in VRs and CBs due to Nonsimultaneous Responses	Remarks
Case Study-1 (Case-1) Data: Table-I Simulation: Fig. 10	VR Tap Operations = 17 520 (per year)	VR Tap Operations = 35 040 (per year)	∗ Additional VR, CB operations due to interactions
Case Study-1 (Case-2): Data: Table-I Simulation: Fig. 11	N/A	CB1 Switching = 17 520 (per year) VR Tap Operations = 26 280 (per year)	∗ Additional VR, CB operations due to interactions
Case Study-2 (Case-3): Data: Tables-I, II Simulation: Fig. 12	VR Tap Operations = 52 560 (per year)	VR Tap Operations = 43 800 (per year)	∗ Additional VR, CB operations & ∗ Voltage rise, due to interactions
Case Study-3 (Case-4): Data: Table-I, III Simulation: Fig. 13	N/A	CB1 Switching = 17 520 (per year) VR Tap Operations = 10 5120 (per year)	∗ Additional VR, CB operations & ∗ Voltage drop, due to interactions

C. Coordinated Voltage Control Strategy and Volt-Var Optimization

A coordinated voltage control strategy or Volt-Var optimization becomes vital to maintain the desired voltage at any point along the feeder for modern distribution system

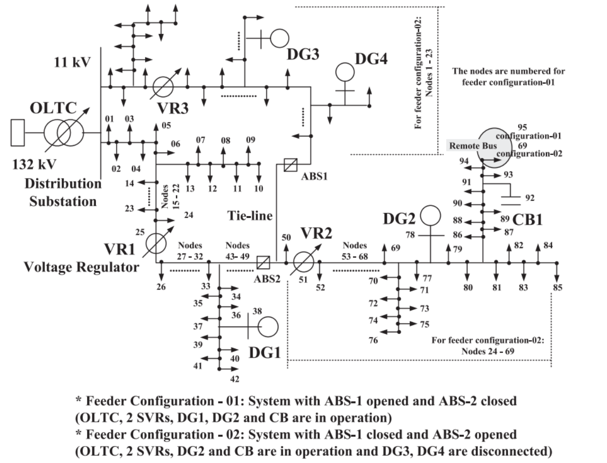

Fig. 7: Topology of a realistic MV distribution feeder system in New South Wales, Australia. [16]

operations. This is typically achieved centrally using a distribution automation system (e.g. SCADA system) or Advanced Distribution Management System (ADMS). VVO as a key function of ADMS is designed to optimize the voltage and reactive power flow in the distribution network using all the possible control devices.

The objective function is typically to minimize the system power loss or energy consumption or combination of both, while the constraints are the maximum current values in feeder lines or transformers and keeping all bus voltages within a range. Besides the traditional standalone Volt-Var controllers and rule-based VVO, the IVVC is the most advanced VVO approach.

The IVVC, also known as DMS model-based VVO approach, uses real-time measurements, a distribution system model and an on-line power flow computation function, and an optimization engine to calculate the optimal set of control actions for all control equipment, and then send the control setpoints to the local controllers embedded in each control equipment via SCADA or a communication link.

In terms of optimization algorithms, they could be analytical methods, numerical methods, heuristic methods, and artificial intelligent (AI) methods. Numerical VVO methods use mixed-integer linear programming, mixed-integer quadratic constrained programming, sequential convex programming, model predictive control, dynamic programming, and ordinal optimization techniques. Most of heuristic methods found in the literature are based on evolutionary optimization algorithms, including genetic algorithms, particle swarm optimization, teaching-learning algorithm, simulated annealing, ant colony optimization, tabu search, shuffled frog leaping algorithm, memetic algorithm, honey bee mating optimization, bacterial foraging algorithm, bee swarm optimization, gravitational search algorithm, and so on. The AI methods include neural network, adaptive neuro-fuzzy inference, and multi-agent system. A detailed review of various VVO methods can be found in [24].

D. Distributed STATCOM

Flexible ac transmission systems (FACTS) have been deployed in the transmission system for voltage control and reactive power compensation, such as SVC using thyristor controlled reactor (TCR) or thyristor switched capacitor (TSC) and UPFC. There is a trend to promote similar control functions using newer self-commutated semiconductor switching devices at the distribution level to create distribution static synchronous compensators (D-STATCOM) and UPQC and to address voltage control and other power quality issues. Some of the D-STATCOM research efforts can be found in [20], [25]–[27].

Furthermore, there is a bold vision to achieve a flatten voltage profile across the entire distribution feeder circuit without communications. One concept is to add more capacitors along the feeder and allow the capacitor banks to be the primary voltage regulating devices while the LTCs of voltage regulators or distribution transformers only address emergency or dramatic voltage changes.

E. Responsive Building Loads

An alternative route to reduce excessive voltage regulation operations and extending the lifetime of existing mechanical-based voltage control equipment (e.g. load tap changes) can be approached from the load control perspective without significant additional capital investment. Driven by the increasing adoption of renewable resources, various demand response strategies, such as [28]–[32], have been developed for responsive building loads to mitigate the impact of solar power fluctuations on the LTCs of distribution transformers and SVRs. Currently, our team at Oak Ridge National Laboratory (ORNL) are developing adaptive control strategies for building HVAC loads to mitigate the impact of solar power minute-to-minute fluctuations on the load tap changers of distribution transformers and step voltage regulators. Since single HVAC load has a relatively slow response, a fleet approach is adopted to seek an aggregation effect and diversified dynamics up to five to ten minutes control resolution. This work demonstrates a technical leapfrog over conventional demand response programs and has a market potential to increase the hosting capacity of solar power in a distribution feeder.

V. CONCLUSIONS

This article provides a review of recent developments in technologies and methods for Advanced Device Management (ADM). Different distribution system architectures, including radial and meshed networks, were reviewed. In addition, some specific distributed voltage control technologies, such as OLTC, SVR, LDC, CVR, and VVO, have been illustrated. Finally, the future trends of smart PV inverters, decentralized voltage control, coordinated voltage control, distributed STATCOM and the concept of responsive building loads were discussed.

ACKNOWLEDGMENT

This material is based upon work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, SunShot National Laboratory Multiyear Partnership (SuNLaMP) program. This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

REFERENCES

[1] Y. P. Agalgaonkar, B. C. Pal, and R. A. Jabr, "Distribution voltage control considering the impact of pv generation on tap changers and autonomous regulators," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 182–192, 2014.

[2] J. Zhao, C. Wang, B. Zhao, F. Lin, Q. Zhou, and Y. Wang, "A review of active management for distribution networks: Current status and future development trends," *Electric Power Components and Systems*, vol. 42, no. 3-4, pp. 280–293, 2014.

[3] N. Gupta, A. Swarnkar, and K. Niazi, "Reconfiguration of distribution systems for real power loss minimization using adaptive particle swarm optimization," *Electric Power Components and Systems*, vol. 39, no. 4, pp. 317–330, 2011.

[4] A. Y. Abdelaziz, R. A. Osama, and S. M. Elkhodary, "Distribution systems reconfiguration using ant colony optimization and harmony search algorithms," *Electric Power Components and Systems*, vol. 41, no. 5, pp. 537–554, 2013.

[5] Y. Xue, I. Sharma, T. Kuruganti, J. Nutaro, J. Dong, M. Olama, and D. Fugate, "Voltage impact analyses of solar photovoltaics on distribution load tap changer operations," in *IEEE North American Power Symposium (NAPS)*, 2017, pp. 1–6.

[6] J. Dong, Y. Xue, T. Kuruganti, I. Sharma, J. Nutaro, M. Olama, J. Hill, and J. Bowen, "Operational impacts of high penetration solar power on a real-world distribution feeder," in *IEEE PES Innovative Smart Grid Technologies Conference (ISGT)*, 2018, pp. 1–6.

[7] G. Fusco and M. Russo, *Adaptive voltage control in power systems: Modeling, design and applications*. Springer Science & Business Media, 2006.

[8] V. Khadkikar, "Enhancing electric power quality using UPQC: A comprehensive overview," *IEEE Transactions on Power Electronics*, vol. 27, no. 5, pp. 2284–2297, 2012.

[9] Y. W. Li and J. He, "Distribution system harmonic compensation methods: An overview of DG-interfacing inverters," *IEEE Industrial Electronics Magazine*, vol. 8, no. 4, pp. 18–31, 2014.

[10] EPRI, "Analysis of extremely reliable power delivery systems: A proposal for development and application of security, quality, reliability, and availability (SQRA) modeling for optimizing power system configurations for the digital economy," EPRI, Palo Alto, CA, 2002. Product ID 051207., Tech. Rep., 2002.

[11] J. D. Bouford and C. A. Warren, "Many states of distribution," *IEEE Power and Energy Magazine*, vol. 5, no. 4, pp. 24–32, 2007.

[12] "Low-voltage network — Wikipedia, the free encyclopedia," 2018, [Online; accessed 19-April-2018]. [Online]. Available: https://en.wikipedia.org/wiki/Low-voltage_network

[13] M. Behnke, W. Erdman, S. Horgan, D. Dawson, W. Feero, F. Soudi, D. Smith, C. Whitaker, and B. Kroposki, "Secondary network distribution systems background and issues related to the interconnection of distributed resources," National Renewable Energy Lab., Golden, CO (US), Tech. Rep., 2005.

[14] H. E. Farag, E. F. El-Saadany, and R. Seethapathy, "The evolution for voltage and reactive power control in smart distribution systems," *International Journal of Emerging Electric Power Systems*, vol. 13, no. 1, 2012.
[15] "Flexible and distributed energy resources, chapter 3: Technology assessments," DOE Quadrennial Technology Review, Tech. Rep., 2015.
[16] D. Ranamuka, A. P. Agalgaonkar, and K. M. Muttaqi, "Examining the interactions between DG units and voltage regulating devices for effective voltage control in distribution systems," *IEEE Transactions on Industry Applications*, vol. 53, no. 2, pp. 1485–1496, 2017.
[17] A. T. Procopiou and L. F. Ochoa, "Voltage control in PV-rich LV networks without remote monitoring," *IEEE Transactions on Power Systems*, vol. 32, no. 2, pp. 1224–1236, 2017.
[18] EPRI, "Grid strategy 2011: Conservation voltage reduction and volt var optimization in the smart grid," EPRI Technical Report 1024482, Nov. 2011., Tech. Rep., 2011.
[19] M. Manbachi, M. Nasri, B. Shahabi, H. Farhangi, A. Palizban, S. Arzanpour, M. Moallem, and D. C. Lee, "Real-time adaptive vvo/cvr topology using multi-agent system and iec 61850-based communication protocol," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 2, pp. 587–597, 2014.
[20] R. Moghe, D. Divan, D. Lewis, and J. Schatz, "Turning distribution feeders into statcoms," *IEEE Transactions on Industry Applications*, vol. 53, no. 2, pp. 1372–1380, 2017.
[21] M. Madrigal, R. Uluski, and K. M. Gaba, *Practical Guidance for Defining a Smart Grid Modernization Strategy: The Case of Distribution (Revised Edition)*. World Bank Publications, 2017.
[22] J. Dixon, L. Moran, J. Rodriguez, and R. Domke, "Reactive power compensation technologies: State-of-the-art review," *Proceedings of the IEEE*, vol. 93, no. 12, pp. 2144–2164, 2005.
[23] I. Kim, R. G. Harley, R. Regassa, and Y. Del Valle, "The effect of the volt/var control of photovoltaic systems on the time-series steady-state analysis of a distribution network," in *IEEE Power Systems Conference (PSC), Clemson University*, 2015, pp. 1–6.
[24] S. Satsangi and G. Kumbhar, "Review on volt/var optimization and control in electric distribution system," in *IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, 2016, pp. 1–6.
[25] X. Luo, Z. Akhtar, C. K. Lee, B. Chaudhuri, S.-C. Tan, and S. Y. R. Hui, "Distributed voltage control with electric springs: Comparison with statcom," *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 209–219, 2015.
[26] J. Das, "Application of statcom to an industrial distribution system connected to a weak utility system," in *IEEE Pulp, Paper & Forest Industries Conference (PPFIC)*, 2016, pp. 124–135.
[27] H. Liao and J. V. Milanović, "On capability of different facts devices to mitigate a range of power quality phenomena," *IET Generation, Transmission & Distribution*, vol. 11, no. 5, pp. 1202–1211, 2016.
[28] H. Hao, T. Middelkoop, P. Barooah, and S. Meyn, "How demand response from commercial buildings will provide the regulation needs of the grid," in *IEEE 50th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, 2012, pp. 1908–1913.
[29] S. H. Tindemans, V. Trovato, and G. Strbac, "Decentralized control of thermostatic loads for flexible demand response," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 5, pp. 1685–1700, 2015.
[30] J. Dong, M. Olama, T. Kuruganti, J. Nutaro, Y. Xue, I. Sharma, and S. M. Djouadi, "Adaptive building load control to enable high penetration of solar pv generation," in *IEEE Power & Energy Society General Meeting*, 2017.
[31] J. Dong, S. M. Djouadi, T. Kuruganti, and M. M. Olama, "Augmented optimal control for buildings under high penetration of solar photovoltaic generation," in *IEEE Conference on Control Technology and Applications (CCTA)*, 2017, pp. 2158–2163.
[32] M. Olama, I. Sharma, T. Kuruganti, J. Dong, J. Nutaro, and Y. Xue, "Spectral analytics of solar photovoltaic power output for optimal distributed energy resource utilization," in *IEEE Power & Energy Society General Meeting*, 2017, pp. 1–5.