2016 the 4th IEEE International Conference on Smart Energy Grid Engineering

A Review of Volt/Var Control Techniques in Passive and Active Power Distribution Networks

Monsef Tahir, Mohammed E. Nassar, Ramadan El-Shatshat, M. M. A. Salama
University of Waterloo
Canada
e-mail: m2tahir@uwaterloo.ca

Abstract—**Volt/Var control problem of distribution systems has been extensively investigated in literature. Many control models and algorithms have been proposed to achieve better system quality, security, reliability, efficiency, loadability, and cost effectiveness. Early distribution systems are built based on centralized power generation which is named passive distribution system (PDS), where power flow is unidirectional. Nowadays, the topology of the distribution system allows for bidirectional power flow which is named active distribution system (ADS) due to the presence of active resources, such as distributed generations (DGs). The complexity of controlling each system depends on the topology and size of the network, as well as the control devices used. However, in general there are mainly two main control strategies used to control power networks: centralized and decentralized. This paper provides a review for both control strategies in the distribution system based on Volt/Var control techniques. It introduces the most commonly used techniques and algorithms in the literature for passive and active distribution systems. Moreover, it provides the reader with a comprehensive review on the common optimization techniques and the different objective functions used in terms of loss minimization, voltage deviation, and minimum control variable operation.**

Keywords-on-load tap changer OLTC; step voltage regulator SVR; shunt or switched capacitor SC; Genetic algorithm GA; particle swarm optimization PSO

I. INTRODUCTION

Recent research in distribution systems addresses issues related to reliability, supply security, equipment capacity utilization, and loss reduction. The way distribution systems are modeled and controlled has become more complex in the presence of distributed generation (DGs), plug-in Electric Vehicles (PEV), advanced voltage control devices and smart protection devices. Hence, distribution network operators (DNOs) experience, in some cases, serious challenges to keep the network efficient and reliable with the existing resources. Voltage and reactive power control in the distribution system are among these crucial challenges. Nowadays, the distribution system is highly loaded and experience high voltage drop on feeders during peak time, which results in violations of allowable voltage limit. In addition, increasing the penetration of renewable based DGs results in high injection of active power that can cause voltage rise in some circumstances. Conventional distribution systems have been constructed and operated based on unidirectional power flow, which is called passive distribution systems (PDS). However, the integration of active components such as DGs, has changed the system from being passive to being an active distribution system (ADS) with bidirectional power flows. ADS is a part of smart grid (SM); that is the new paradigm of distribution systems depends on communication infrastructures, smart meters, and advanced controllers designed to meet customers and utilities preferences efficiently.

Volt/Var control, which is the core of this review paper, has been widely explored and studied by researchers and implemented by utilities to improve the performance of the distribution networks and satisfy voltage requirements. Research has been conducted on PDS, and more recently on ADS to propose advanced voltage and reactive power control strategies. Usually, Volt/Var control in distribution systems is conducted using control devices such as on-load tap changing (OLTC), step voltage regulator (SVR), shunt capacitor (SC), and inverter-interfaced DGs. Volt/Var control strategies in distribution systems are categorized to centralized and decentralized. Centralized control approach allows two-way communication between a supervisory controller and other systems devices. Whereas, in the decentralized control approach, control problems are solved locally inside zones or specified areas and the communication is used between peers. This paper provides a review for both control strategies in the distribution system and their applicability. This paper presents the techniques and algorithms introduced in the literature for passive and active distribution systems. Moreover, it introduces to the reader a comprehensive review for the most used optimization techniques, objective functions and constraints.
This paper is structured as following: section II lists commonly used control devices in power network and the way they are used for voltage support. Section III is an introduction to the classification of control strategies in terms of centralized and decentralized approaches. Section IV and section V review the centralized and decentralized Volt/Var control techniques in passive and active distribution systems respectively. The discussion of the trends and control strategies reviewed in this paper is presented in section VI. Finally, the conclusion is proposed in section VII.

II. CONTROL VARIABLES

Distribution systems usually consist of the following components: sources of power (mainly substation transformer and DGs), feeders and laterals to deliver power, protection and control devices, loads, and communication devices. The control devices or variables, as used by many researchers, play the main role in terms of controlling both voltage and power. Basically, distribution system voltage control variables are OLTC, SVR, SC, inverters of distributed generator, and load curtailment (LC) that is used during emergency cases to avoid system collapse. Those are the main control variables used to regulate system voltage and control the reactive power flow in order to keep the system secure, reliable, and cost effectiveness. The cost effectiveness is meant by the reduction of system's power losses, loss of load (LOL) and investment in system upgrades. The control devices such as OLTC and SVR are used to rise or down the voltage based on line drop compensator (LDC) control method. Shunt capacitor usually operates based on time, voltage, current or thermal control modes to support lower voltages by injecting reactive power. DGs used to operate as unity power factor, however; recently DGs contribute in voltage support by controlling the inverters interfaced to injective reactive power.

III. CLASSIFICATION OF CONTROL TECHNIQUS

Before going through the main control strategies for Volt/Var control in distribution systems, a short introduction to distribution automation provides a clear picture to what is meant by Volt/Var control in distribution system. Distribution automation is defined as "the ability to automatically and remotely monitor, control, manipulate and coordinate distribution components in real time modes" [1]. It is also defined by (IEEE) as "systems that enable an electric utility to monitor, coordinate, and operate distribution components in a real time mode from remote locations" [1]. To achieve this control, there are two main control strategies used in power networks: centralized and decentralized control. The implementation of each strategy depends on network topology and available communication infrastructure in the system. Centralized control strategy is the most used control strategy in the literature [2][3] . Decentralized control strategy tends to solve Volt/Var control problems locally or in specified zone, where control agents communicate with each other and coordinated by a distributed (decentralized) controller. This distributed control fits with the requirements of smart grids and offers easy control. The decentralized control techniques require no expensive investment in the communication infrastructure. In contrast, centralized control techniques depend heavily on communication infrastructure, where all information from system's components are sent to a centralized controller that is used to solve an optimization problem and determine the optimal setting of each control variable. These settings are communicated back to the installed control devices which represent heavy dependency on the communication medium and hence affect system's reliability. Generally, control modes are classified into two categories: rule based mode and network model based mode [4]. In the rule based mode, the controller employs a set of conditions and operates the control variables according to these conditions or rules using historical information in conjunction with online measurements of the system. In the network model control mode, the controller usually solves an optimization problem to find the optimal dispatching schedule of control variables based on system topology; online measurement statistical information, and the network current state calculated by solving power flow problem [4]. Fig. 1 depicts the categories of control strategies of different distribution systems.

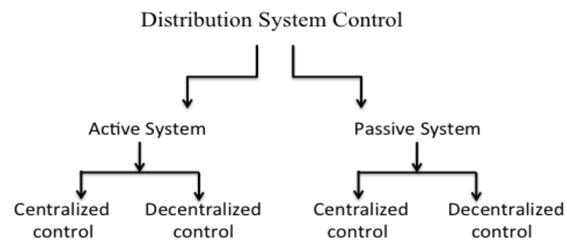

Figure 1. Simple control strategy of distribution system

In this review, the classification of the presented papers will be based on the objective function to be optimized for Volt/Var control. Commonly, there are three types of objective function used: losses minimization, voltage deviation, and switching operations. Papers will be presented based on the similar optimization problem used.

IV. PASSIVE DISTRIBUTION SYSTEM (PDS)

The passive distribution system (PDS) is a typical distribution system feeds solely from a distribution substation that services one or more primary feeders. In most cases, those feeders are radial, which means that there is only one direction for power flow from the distribution substation to users [5]. PDS is the early days' model of distribution network that serves loads through feeders based on centralized generation without integration of distributed renewable energy resources. Radial networks are the most commonly used topology in distribution systems in North America. In the passive distribution networks, Volt/Var control schemes depend mainly on load tap changer transformers, step voltage regulators, and switched capacitors. A typical passive distribution system is shown in fig. 2. Power is supplied from the substation transformer in one direction to the load through a transmission line. Shunt capacitor usually is placed close to load center to inject reactive power into the system to support system's voltage during peak load periods.

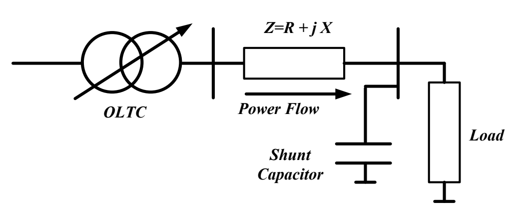

Figure 2. Passive distribution system.

A. Centralized Control of PDS

The centralized control is widely applied in passive distribution systems. Distributed control devices such as OLTCs, SVRs, and SCs placed in distribution networks are controlled by one supervisory controller in this centralized mode. Thus, the supervisory controller continuously tracks network's status and react accordingly; hence if any disturbance takes place, appropriate setting information is sent to the control devices to bring the system back to its normal operating condition. Usually, the information sent to the control devices include the optimal setting of each device to regulate the bus voltage, alleviate component capacity, or minimize system losses subjected to devices and system constraints. Numerous papers in literature discussed the Volt/Var control problem for distribution systems and proposed various system models and control techniques. Different mathematical formulations for the optimization problem are presented and solved using various solvers. The problem can be formulated to minimize the total switching operations and find the corresponding optimal dispatching schedule for control devices. numerous research papers tackled this approach from different perspectives as in [6]-[9]. The optimal dispatching of OLTCs and SCs has been achieved in is work based on hourly load forecasting for the next 24 hours. Thus, Volt/Var control to maintain system voltages within certain limits has been achieved with the minimum control effort from the control devices, which maximizes the life expectancy of these devices. Moreover, solving power flow problem that estimates buses voltage and lines flow, based on load forecasting and incorporates these results in finding the optimal setting of control devices makes the technique more efficient and reliable. The formulated optimization problems presented in [6]-[9] are solved using fuzzy and neural networks techniques. Moreover, the optimization problem was formulated to minimize the voltage deviation to keep bus voltage as close as possible to a predefined value. This approach was proposed as a centralized control mode in [6]-[8], [10]. where [6]-8] used minimum switching operation of control devices as an objective function in addition to the voltage deviation minimization. Again optimal dispatching of control devices such as OLTCs, and SCs is achieved by solving the power flow problem over the next 24 hours and solving the optimization problem subjected to system's constraints. The minimization of system losses is considered as an objective function to achieve optimum voltage control as in [10]-[13]. In this work, the dispatch of the OLTC, SVRs and switched capacitors was based on feeder's hourly load forecasting and used for achieving the Volt/Var control. Dynamic programming, Fuzzy logic, and neural networks techniques are used to solve the formulated optimization problems. Also, substation transformer reactive power flow is minimized while the number of switches of each capacitor is reduced. Therefore, the voltage is maintained within pre-specified range with minimum control actions.

B. Decentralized Control of PDS

In terms of decentralized control modes, very few papers tackled this control strategy in PDS as it is not preferable technique in radial passive systems. Unlike centralized control, decentralized control does not need extensive communications between controllers as the problem can be solved locally with minimum communication infrastructure. The development of a suboptimal decentralized feedback control strategy for the static VAR systems (SVSs) was introduced in [14]. These systems were optimally placed at interconnected power networks to reduce voltage violations in the system resulting from network disorder. This approach uses the voltage deviation as the objective function to be minimized. A novel zonal coordinated secondary voltage control technique using grey prediction controllers is introduced in [15] where the problem was formulated as a quadratic programming problem. The objective was minimizing the voltage deviation at critical nodes and keep necessary reactive power reservation. The proposed model takes into consideration the variation of reactive power in the system by grey model to develop an enhanced control approach. The developed control approach employed more measurements to compensate the impact by other neighbor zones.

V. Active Distribution System

In contrast to the traditional distribution network, smart grid, which is the new paradigm of the conventional distribution system, includes centralized and distributed power generation produced by dispatchable and renewable energy sources. Moreover, it integrates distributed and active resources (i.e. generation, loads, storages) into power system and can be characterized by a unidirectional and bidirectional power flow [16]. The existence of DGs has changed the operation of distribution network from being passive with centralized generation to active system with distributed generation and bidirectional power flow. A global definition from [17] "states that ADNs are distribution networks that have systems in place to control a combination of distributed energy resources (generators, loads, and storage). Distribution system operators (DSOs) have the possibility of managing the electricity flow using a flexible network topology. Distributed energy resources (DERs) take some degree of responsibility for system support, which will depend on a suitable regulatory environment connection agreement". Fig. 3 shows a simple diagram of active distribution network that consists DERs.

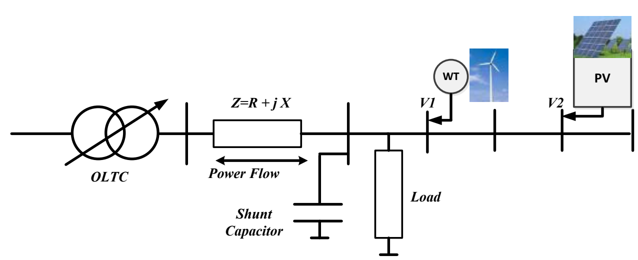

Figure 3. Active distribution system.

However, integration of renewable energy sources creates significant technical and economic problems to distribution network. Regardless of their benefits, such as losses reductions, voltage support, and distribution capacity release [18]-[21], the high penetration of renewable distributed generation leads to undesirable voltage fluctuation, which may lead to excessive operation of OLTC, SVR, and SC.

In literature, many centralized and decentralized control strategies or distributed control, which falls into decentralized mode, are presented for active distribution networks. Authors of [22] compared the centralized and distributed control strategies in term of voltage regulation under the increase capacity of distributed generation in the distribution system. They performed simulations and studied the impact of DGs connected on voltage violation, losses, and cost.

A. *Centralized Control of ADS*

Numerous research works proposed the centralized control as a solution for the Volt/Var control problem considering or neglecting the high penetration of distributed renewable generation in distribution systems. Volt/Var control problem is formulated as an optimization problem based on various objective functions subjected to system's constraints. As classified earlier in the centralized control of PDS, grouping research efforts of ADS will be based on the formulation of the optimization problem used. Considering an objective of minimizing the total switching operations and hence finding the optimal dispatching schedule or optimal coordination of control devices, The Volt/Var control problems were investigated in [23]-[27]. Here, authors investigated and solved Volt/Var control problem targeting the minimum control effort of control variables. Additionally, less switching operations that minimizes the associated operation costs and increases the expected life of the control devices was achieved. These optimization problems are usually formulated as mixed-integer nonlinear programming (MINLP) and solved using heuristic search techniques such as PSO and ANN as in [23], [27]. Control variables such OLTC, SVR, SC, FC, and DG are coordinated to reach optimal scheduling scenario that minimizes switching operation as well as maintains the system voltage within pre-specified limits. Optimal scheduling is determined based on the hourly forecasting of DGs output power and system loads for the next day. The DGs are employed as voltage control variables in coordination with other variables by providing a percentage of its output power as a reactive power. Although, DGs usually operated at unity power factor, recently this fact changed and DGs are allowed to operate at lower power factor to support system voltage when other control variables are exhausted. Another type of research papers investigated and proposed solutions for Volt/Var control problem by formulating problems to minimize total system losses considering system operational constraints and physical boundaries of the control devices [23], [24], [27] [28]-[35]. Authors here applied centralized control strategy in active distribution systems to control system voltages by controlling the flow of the reactive power. Control variables such as OLTC, SC, SVR, and DGs are optimally set and dispatched to meet network operation and components constraints. Formulating the optimization problem to minimize power losses in the network is commonly used to enhance system efficiency and hence reduce the operation cost. The hourly forecasting output power of renewable energy sources and demands are performed as in [23], [29], [31], [32], where power flow problem needs to be solved for a day ahead to determine the optimal setting of the control devices at each hour. The optimization problems in [23], [34] are formulated as MINLP and solved by heuristic techniques subjected to system constraints such as the maximum allowable operation number of OLTC, SC and reactive power limit of capacitors and DGs. Additionally, high penetration level of renewable sources are investigated in [29], [33] and solutions suggested to use controllable loads and microgeneration shedding as well as coordination among control devices. Minimizing voltage deviation from a nominal value due to the variation in loading conditions or high penetration of renewable source is another approach of setting the objective function used in Volt/Var control technique. Authors of [25], [30], [36] proposed voltage control methodology considering LRT, SVR, and inverters interfaced DGs in the network by minimizing voltage deviation as an objective. Usually, this objective function is considered when there is a high penetration level of intermittent power sources this formulation results in the reduction of the high voltage that may occur at the DG interconnection point. Different objective functions may be used as presented in[37] where authors suggested a Volt/Var control operational model to maximize the profit of the distribution company under the high penetration of renewable resources such as wind power. The optimization problem was formulated as an MINLP problem and solved using genetic algorithm (GA) in centralized control mode. A methodology for generation curtailment due to voltage constraints was addressed in [38]. The approach aims to satisfy system constraints by curtailing distributed renewable sources in the case of high voltage imposed by reverse power flow considering a voltage sensitivity factor. A methodology for incorporating charging station of PEV in controlling the distribution system voltage in two steps through a centralized controller and under the high penetration level of PVs was introduced in [39]. In general, centralized Volt/Var control problem in ADS are usually solved using one of the aforementioned three objective functions or a combination between them depending on the type and requirement of the problem. Other approaches choose different objective functions based on problem type such as maximizing the output power from DERS or curtailing them to satisfy system constraints.

B. *Decentralized Control of ADS*

Decentralized control is another type of control strategies used in active distribution system for Volt/Var control. Solving the optimization problem in decentralized control mode is similar to the one used in centralized control mode. However, in decentralized control model usually there is more than one optimization problem to be solved. If distribution system is zoned or sectionalized, then each zone or local control area requires an objective function to be optimized with or without coordination with other local areas.

In large active distribution systems, the number of control variables is very high and the computational time for solving one centralized optimization problem is long, which is not preferable when performing online control. Therefore, large systems are divided to subsystems, and hence optimization problem is divided to subproblems that can be solved swiftly. In literature, research papers tackled Volt/Var control problem using decentralized control mode. Numerous research work applied power loss minimization as an objective function as in [40]-[42]. Authors of these papers investigated and proposed solutions to the problem of having high penetration of renewable energy resources installed in distribution system. A decentralized control approach was applied to coordinate control variables in order to improve the voltage profile in the presence of high DGs output power. Moreover, minimizing of the voltage deviation was considered as an objective function in a decentralized fashion as in [40], [42], [43]-[47]. In [40], a decentralized control approach is used to coordinate LRT, SVR,SC, SR for optimal voltage profile with the presence of PV system using FFNN trained and optimal data generated by Genetic Algorithm. Authors of [43], proposed a decentralized reactive power control considering remote terminal units (RTUs) installed at each DG and shunt capacitors. Coordination among RTUs through communication channels was implemented to regulate voltage profile and minimize system losses. In [44], power factor control of DGs and multi-agent technology considering the response delay of shunt capacitor and OLTC are used to regulate bus voltage. While in [45], two stages control methodology for voltage control at busbar was proposed. In the first stage, the required reactive power from a connected DG unit to support a violated busbar voltage is estimated. At the second stage, if the violated busbar voltage cannot be regulated locally by the connected DG due to its capacity, a distributed algorithm exchange information with other controllers at neighbor busbar to compensate the reactive power to bring voltage to its desired limit. In addition, [46]proposed the control of the voltage rise due to the integration of distributed generation. The controller optimally limits the reactive power injected by DGs to a level prevents voltage violation and keeps the conventional voltage control approach runs by the distribution network operators. In [47], a decentralized voltage control scheme is proposed to handle the problem of high penetration of renewable generation. The suggested control approach aims to effectively control traditional voltage regulators OLTC, and SVR by using multi-agent control system that controls single areas locally rather than centralized control.

VI. Discssion

Different Volt/Var control methodologies and techniques are investigated and implemented in literature. The new infrastructures of a distribution system depend on communications and smart meters to play an important role in the effectiveness of a successful control strategy. The way of controlling a passive distribution system differs from an active distribution system. Passive systems controlled based on unidirectional power flow, while active system are controlled based on bidirectional power flow due to the existence of DGs. For some distribution networks, it is feasible to apply centralized control if there is a full communication channel between all control equipment and the centralized controller. In contrast, the decentralized control approach can be applied locally or for specific zones given that only communications are needed between local control devices. In addition to the both control approaches, some of the challenges distribution system operators experience are engaging all the control devices of the network for controlling without conflict or complexity. In literature, many formulations and tools are used to handle the collaboration problem among control equipment without conflict. Moreover, the existence of renewable energy sources and the unpredictable output power as well as variable demands may cause changes in the operational situation. In the traditional distribution networks, the OLTC and SC regulate the violated voltages based on the concept of line drop compensation (LDC) without considering the stream of the power flow caused by DGs and hence, more frequent or unnecessary operations of control devices can happen. Another issue is the high penetration of renewable sources into the distribution system which causes voltage fluctuation at the connection point due to the high variation of the output power from the RESs. Furthermore, the high penetration reverses the power flow in some cases, causing inappropriate voltage control and excessive switching actions.

In literature many papers tackled the problem of high penetration of distributed generation and their impact on distribution system and more specifically on voltage violation. Also, proper forecasting techniques of loads and renewable sources output in order to predict the actual demand and output power respectively played an important role in appropriate control strategy. In addition, researchers solved the problem of excessive or inappropriate control actions under the high installation of RESs by minimizing the control efforts as a function of operational cost with or without coordination with DGs output subject to system constraints.

VII. Conclusion

A review of voltage and reactive power control in distribution system has been conducted. An introduction to the control devices used to regulate system voltage and compensate reactive power, as well as classification of control techniques is introduced. The classification of the control techniques is based on the most and common used type of control modes in distribution system in both ADS and PDS, which are centralized and decentralized control modes. Centralized control schemes are more popular in literature due to their capability of solving one optimization problem. The centralized control schemes include all system control devices and assure, in most cases, the optimal setting of these devices. However, a high investment is needed in the communication infrastructure of power system to achieve appropriate control strategy for the centralized control. On the other hand, decentralized control technique solves Volt/Var control problems in systems locally, where sub-objective functions are solved independently. Decentralized control techniques do not need full communication infrastructures but they need the minimum inside zonal or specified control area. In passive distribution system, most of the control strategies are done based on centralized control, whereas very few publications tackled the decentralized one. In contrast, in active distribution system, application of centralized and decentralized control is used widely due to the presence of DGs, where a network can be zoned or centralized easily.

REFERENCES

[1] D. Gruenemeyer, "Distribution automation: How should it be evaluated?," in *[Proceedings] 1991 Rural Electric Power Conference. Papers presented at the 35th Annual Conference*, 1991, pp. C3/1–C310.

[2] W. R. Cassel, "Distribution management systems: Functions and payback," *IEEE Trans. Power Syst.*, vol. 8, no. 3, pp. 796–801, 1993.

[3] "Automated distribution comes of age.pdf." .

[4] I. Roytelman and V. Ganesan, "Coordinated local and centralized control in distribution management systems," *IEEE Trans. Power Deliv.*, vol. 15, no. 2, pp. 718–724, 2000.

[5] W. Kersting, Distribution system modeling and analysis. 2012.

[6] T. K. Wong, C. M. Mak, and T. S. Chung, "Co-ordination of transformer tap and capacitor operation for reactive power voltage control in a distribution primary substation," *Adv. Power Syst. Control. Oper. Manag. 2000. APSCOM-00. 2000 Int. Conf.*, vol. 2, no. October, pp. 479–485 vol.2, 2000.

[7] R. Liang and Y. Wang, "Fuzzy-based reactive power and voltage control in a distribution system," *IEEE Trans. Power Deliv.*, vol. 18, no. 2, pp. 610–618, 2003.

[8] Y. Y. Hsu and F. C. Lu, "A combined artificial neural network-fuzzy dynamic programming approach to reactive power/voltage control in a distribution substation," *IEEE Trans. Power Syst.*, vol. 13, no. 4, pp. 1265–1271, 1998.

[9] J. J. Paserba, D. J. Leonard, N. W. Miller, S. T. Naumann, M. G. Lauby, and F. P. Sener, "Coordination of a distribution level continuously controlled compensation device with existing substation equipment for long term VAr management," *IEEE Trans. Power Deliv.*, vol. 9, no. 2, pp. 1034–1040, Apr. 1994.

[10] R. Liang and C. Cheng, "Dispatch of main transformer ULTC and capacitors in a distribution system," *Power Deliv. IEEE Trans.*, 2001.

[11] F.-C. Lu and Y.-Y. Hsu, "Reactive power/voltage control in a distribution substation using dynamic programming," *Gener. Transm. Distrib. IEE Proceedings-*, vol. 142, no. 6, pp. 639–645, 1995.

[12] Z. Gu and D. T. Rizy, "Neural networks for combined control of capacitor banks and voltage regulators in distribution systems," *IEEE Trans. Power Deliv.*, vol. 11, no. 4, pp. 1921–1928, 1996.

[13] Y.-Y. Hsu and H.-C. Kuo, "Dispatch of capacitors on distribution system using dynamic programming," *IEE Proc. C Gener. Transm. Distrib.*, vol. 140, no. 6, p. 433, 1993.

[14] M. Brucoli, F. Torelli, and M. Trovato, "A decentralised control strategy for dynamic shunt VAr compensation in interconnected power systems," *IEE Proc. C Gener. Transm. Distrib.*, vol. 132, no. 5, p. 229, 1985.

[15] P. Ye, B. Yao, and J. Song, "Coordinated secondary voltage control among zones based on grey prediction controllers," *Proc. IEEE Power Eng. Soc. Transm. Distrib. Conf.*, vol. 2005, pp. 1–4, 2005.

[16] L. F. Ochoa, C. J. Dent, and G. P. Harrison, "Distribution Network Capacity Assessment□: Variable DG and Active Networks," vol. 25, no. 1, pp. 87–95, 2010.

[17] C. D'Adamo, S. Jupe, and C. Abbey, "Global survey on planning and operation of active distribution networks - update of CIGRE C6.11 working group activities," in *IET Conference Publications*, 2009, pp. 555–555.

[18] P. P. Barker and R. W. De Mello, "Determining the impact of distributed generation on power systems. I. Radial distribution systems," *Power Eng. Soc. Summer Meet. 2000. IEEE*, vol. 3, no. c, pp. 1645–1656 vol. 3, 2000.

[19] X. Xintao and X. Junzi, "Evaluation of Potential for Developing Renewable Sources of Energy to Facilitate Development in Developing Countries," *Power Energy Eng. Conf. (APPEEC), 2010 Asia-Pacific*, pp. 10–12, 2010.

[20] R. A. R. Walling, R. Saint, S. Member, R. C. Dugan, J. Burke, L. A. Kojovic, and S. Member, "Summary of Distributed Resources Impact on Power Delivery Systems," vol. 23, no. 3, pp. 1636–1644, 2008.

[21] V. Knyazkin, V. Knyazkin, and T. Ackermann, "Interaction between Distributed Generation and the Distribution Network□: Operation Aspects," pp. 1357–1362, 2002.

[22] P. N. Vovos, A. E. Kiprakis, A. R. Wallace, and G. P. Harrison, "Centralized and distributed voltage control: Impact on distributed generation penetration," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 476–483, 2007.

[23] W. Sheng, S. Member, K. Liu, S. Cheng, X. Meng, and W. Dai, "A Trust Region SQP Method for Coordinated Voltage Control in Smart Distribution Grid," vol. 7, no. 1, pp. 381–391, 2016.

[24] F. a Viawan and D. Karlsson, "Coordinated voltage and reactive power control in the presence of distributed generation," *Power Energy Soc. Gen. Meet. - Convers. Deliv. Electr. Energy 21st Century, 2008 IEEE*, pp. 1–6, 2008.

[25] T. Van Cutsem and G. Valverde, "Coordinated voltage control of distribution networks hosting dispersed generation," *Electr. Distrib. (CIRED …*, 2013.

[26] D. Ranamuka, A. P. Agalgaonkar, K. M. Muttaqi, and S. Member, "Online Voltage Control in Distribution Systems With Multiple Voltage Regulating Devices," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 617–628, 2014.

[27] D. Jakus, J. Vasilj, and P. Sarajcev, "Voltage control in MV distribution networks through coordinated control of tap changers and renewable energy sources," *2015 IEEE Eindhoven PowerTech, PowerTech 2015*, 2015.

[28] R. A. Jabr, I. Džafić, and S. Member, "Sensitivity-Based Discrete Coordinate-Descent for Volt / VAr Control in Distribution Networks," pp. 1–9, 2015.

[29] Z. Ziadi, S. Member, S. Taira, S. Member, M. Oshiro, and S. Member, "Optimal Power Scheduling for Smart Grids Considering Controllable Loads and High Penetration of Photovoltaic Generation," vol. 5, no. 5, pp. 2350–2359, 2014.

[30] Z. Ziadi, M. Oshiro, T. Senjyu, A. Yona, N. Urasaki, T. Funabashi, and C. H. Kim, "Optimal voltage control using inverters interfaced with PV systems considering forecast error in a distribution system," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 682–690, 2014.

[31] M. Oshiro, K. Uchida, T. Senjyu, and A. Yona, "Voltage control in distribution systems considered reactive power output sharing in smart grid," pp. 458–463, 2010.

[32] M. Z. C. Wanik, I. Erlich, A. Mohamed, and H. Shareef, "Predictive var management of distributed generators," *2010 9th Int. Power Energy Conf. IPEC 2010*, pp. 619–624, 2010.

[33] A. G. Madureira and J. a. Peças Lopes, "Coordinated voltage support in distribution networks with distributed generation and microgrids," *IET Renew. Power Gener.*, vol. 3, no. 4, p. 439, 2009.

[34] M. Sarmin, W. Nakawiro, and M. Wanik, "Coordinated Voltage Control in Distribution Network with Renewable Energy Based Distributed Generation," *Engineering*, vol. 2013, no. January, pp. 208–214, 2013.

[35] Y. Liao, W. Fan, A. Cramer, P. Dolloff, Z. Fei, M. Qui, S. Bhattacharyya, L. Holloway, and B. Gregory, "Voltage and var control to enable high penetration of distributed photovoltaic systems," *2012 North Am. Power Symp. NAPS 2012*, 2012.

[36] M. Oshiro, K. Tanaka, T. Senjyu, S. Toma, A. Yona, A. Y. Saber, T. Funabashi, and C.-H. Kim, “Optimal voltage control in distribution systems using PV generators,” *Int. J. Electr. Power Energy Syst.*, vol. 33, no. 3, pp. 485–492, 2011.

[37] M. Farrokhi, M. Fotuhi-Firuzabad, and. S. Heidari, “A novel voltage and Var control model in distribution networks considering high penetration of renewable energy sources,” in *2015 23rd Iranian Conference on Electrical Engineering*, 2015, pp. 1709–1714.

[38] P. H. and M. L. J. Skea, D. Anderson, T. Green, R. Gross, “Intermittent renewable generation and the cost of maintaining power system reliability,” *Gener. Transm. Distrib. IET*, vol. 1, no. 2, p. 324, 2007.

[39] L. Cheng, Y. Chang, and R. Huang, “Mitigating Voltage Problem in Distribution System With Distributed Solar Generation Using Electric Vehicles,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1475–1484, 2015.

[40] S. Toma, T. Senjyu, Y. Miyazato, A. Yona, K. Tanaka, and C.-H. Kim, “Decentralized voltage control in distribution system using neural network,” *2008 IEEE 2nd Int. Power Energy Conf.*, no. PECon 08, pp. 1557–1562, 2008.

[41] V. Calderaro, G. Conio, V. Galdi, G. Massa, and A. Piccolo, “Optimal decentralized voltage control for distribution systems with inverter-based distributed generators,” *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 230–241, 2014.

[42] A. R. Malekpour, A. Pahwa, and B. Natarajan, “Distributed Volt / Var Control in Unbalanced Distribution Systems with Distributed Generation,” pp. 0–5, 2014.

[43] M. E. Elkhatib, R. El Shatshat, and M. M. A. Salama, “Decentralized reactive power control for advanced distribution automation systems,” *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1482–1490, 2012.

[44] T. Tsuji, T. Hashiguchi, T. Goda, K. Horiuchi, and Y. Kojima, “Autonomous decentralized voltage profile control using multi-agent technology considering time-delay,” *2009 Transm. Distrib. Conf. Expo. Asia Pacific*, pp. 1–8, 2009.

[45] B. a. Robbins, C. N. Hadjicostis, and A. D. Dominguez-Garcia, “A Two-Stage Distributed Architecture for Voltage Control in Power Distribution Systems,” *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1470–1482, 2013.

[46] P. M. S. Carvalho, P. F. Correia, and L. a F. Ferreira, “Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks,” *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 766–772, 2008.

[47] Y. Zoka, N. Yorino, M. Watanabe, and T. Kurushima, “An optimal decentralized control for voltage control devices by means of a multi-agent system,” *2014 Power Syst. Comput. Conf.*, no. 1, pp. 1–8, 2014.