Distributed and Decentralized Voltage Control of Smart Distribution Networks: Models, Methods, and Future Research

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***Abstract*—The future grid is evolving into a smart distribution network that integrates multiple distributed energy resources ensuring at the same time reliable operation and increased power quality. In recent years, many research papers have addressed the voltage violation problems that arise from the high penetration of distributed generation. In view of the transition to active network management and the increase in the quantity of collected data, distributed control schemes have been proposed that use pervasive communications to deal with the complexity of smart grid. This paper reviews the recent publications on distributed and decentralized voltage control of smart distribution networks, summarizes their control models, and classifies the solution methodologies. Moreover, it comments on issues that should be addressed in the future and the perspectives of industry applications.**

***Index Terms*—Decentralized voltage control, distributed voltage control, distribution networks, smart grid, voltage management, voltage regulation.**

I. INTRODUCTION

VOLTAGE management of smart distribution networks has a prominent position in the research on smart grids. The intermittent nature of renewable generation causes fast voltage fluctuations that are difficult to handle and deteriorate the power quality. Moreover, the large R/X ratio of medium voltage (MV) and especially low voltage (LV) network makes the distribution lines particularly prone to voltage deviations due to the variable generated active power. The use of plug-in electric vehicles (PEV) adds another challenge to the operation of the network because of the abrupt load increase during their charging.

A serious impediment to higher DG integration is the voltage rise and the bi-directional flows due to active power injections at the distribution level that can interfere with the operation of tap changers, since the automatic relay voltage reference is no longer indicative of the voltage profile throughout the feeder [1]. This could lead to excessive use of tap changer (hunting effect) that wears the devices and affects severely the voltage stability.

The current utility-side voltage regulation with conventional Voltage/VAR control devices (VVC devices) cannot respond well and fast to the voltage limits violations that may occur due to DG power injection and PEV charging. However, modern information and communication technologies (ICT) and developments in power electronics technology create new possibilities in controlling and efficiently accommodating the small scale generation at the distribution level [2]. As a result, flexible control schemes have emerged trying to mitigate the voltage problems that occur in distribution grids. Many of these strategies have a centralized control architecture, which means that all the data are gathered in a single point, where a central processor makes the control decisions regarding the whole distribution network. The pursuit for real-time (nearly instantaneous) control motivated the development of efficient control schemes that can distribute the tasks among multiple controllers, each of which solves a smaller subpart of the problem. This way, the optimization problem can be frequently re-solved, as is actually needed. Moreover, the solution of the sub-problems does not require global information, in contrast with the solution at a central hub, which can be affected by potential data unavailability (e.g., due to privacy matters or lack of metering infrastructure).

A review of distributed control techniques can be found in [3], which focuses on the microgrid control and surveys voltage control methods among other relevant applications. The scope of this paper is to review communication-based non-centralized control schemes that were applied specifically in voltage regulation of distribution networks. The contribution of this paper is twofold. First, this paper introduces specific definitions of distributed and decentralized control schemes, in the context of smart distribution networks. It attempts for the first time, as far as the authors know, to clarify the distinction between the control schemes, classifying also the reviewed publications according to these new definitions. Furthermore, it presents a concise and comprehensive taxonomy of the proposed control models along with a detailed classification of the solution methodologies that have been applied.

The structure of this paper is as follows. Section II provides a classification of the existing control schemes

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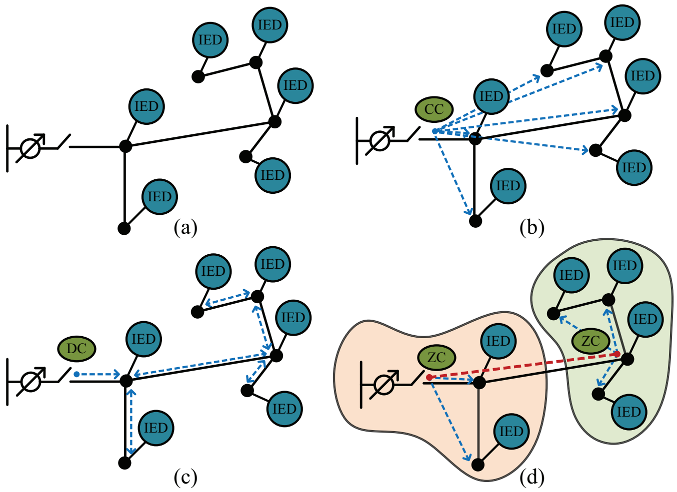

Fig. 1. Classification of control schemes based on their communication network: a) no communication, b) centralized control, CC: central coordinator, c) distributed control, DC: distributed coordinator (grid operator interface), and d) decentralized control, ZC: zone coordinator.

based on communication. Section III describes the control models of distributed/decentralized control. Section IV discusses the decomposition of the voltage control problem. Section V presents and evaluates the solution methodologies, and it also presents the proposed taxonomy. Section VI highlights important issues for future research on voltage control and Section VII comments on the possibilities of industry application. Conclusions are drawn in Section VIII.

II. Classification Based on Communication

The applied control schemes can be classified into two major categories: i) communication-based and ii) autonomous (or local). An additional classification of the first category can be defined based on the fashion of exchanging the information between the participating entities as: i) centralized, ii) decentralized, and iii) distributed. The hybrid combination among those schemes or between autonomous and communication-based control is also possible.

In *local control*, shown in Fig. 1(a), the controllers (marked as intelligent electronic devices (IEDs) in Fig. 1) only use measurements at the point of common coupling (PCC) and no other remote measurement on the grid [4]–[6]. These schemes can respond fast to DG variability and are not affected by communication failures. However, since there is no coordination, they do not exploit the full potential of the distributed controllable components, which can result in globally non-optimal control solutions.

In *centralized control*, shown in Fig. 1(b), there is one central coordinator that receives all the required measurements of the grid, possibly through smart meters and/or remote terminal units, retrieves the solution to the control problem and communicates back the set-points to the IEDs [7], [8]. The central coordinator is the only network component that can initiate a control action.

In *distributed control*, shown in Fig. 1(c), the IEDs are not remotely dispatched (e.g., [9] and [10]). Instead, all IEDs cooperate together to reach a collective decision according to the goals that have been set (i.e., by the grid operator or the end-user). Each controller needs to communicate only with neighboring nodes and hence global information of the grid (i.e., the state of all nodes) is not required in order to determine the control decision. The objective of a distributed coordination structure is to reach a self-organized power grid, which has the ability to cope effectively with the problems that might occur using only local interactions and providing "plug and play" capability among other advantages.

The *decentralized control*, shown in Fig. 1(d), refers to an intermediate state between centralized and distributed control, which means that control is partly centralized and partly distributed regarding the decisions, command/information signals or computation. A classic case of decentralized control is the network partitioning into zones (e.g., [11] and [12]), where each zone is equipped with its own controller (zone coordinator) that functions in the same way as a central coordinator in its area and these controllers might be loosely coupled for coordination purposes, in resemblance with distributed control, to achieve a specific goal.

Distributed and decentralized schemes can offer a robust and flexible control of the distribution network [13]. Moreover, they can deal with limited communication and low bandwidth and are much less affected by faults in the communication lines. All these qualities make them very attractive for smart grid application.

III. Control Models

A. Coordination Scheme

The control schemes that are of interest in this review paper are those that have distributed or decentralized coordination among the controllers or those that combine distributed/decentralized control with other control schemes.

It is important to note that although there are papers that suggest distributed or decentralized control without communication, e.g., [14]–[16], the classification in this paper will follow the definitions provided in Section II. Also, the proposed classification will make use of these definitions to set the distinction between distributed and decentralized control, so papers that assume communication among neighbors to transfer or receive information from far connected nodes will not be classified as distributed (e.g., [17] and [18]).

B. Distribution System Modeling

Classic AC power flow equations are used to formulate the bus injection model (BIM) of the distribution system operation [19]. Several assumptions have been used in distribution system modeling (DSM) in order to simplify the solution of the problem, including the small voltage angle difference between buses [20], lossless power lines [20], constant R/X ratio along the feeders (e.g., [10] and [12]) or the electric proximity between DG units (e.g., [21] and [22]), which is a typical assumption adopted for microgrids. The DC BIM has also been used for DC microgrids modeling.

Another formulation is the branch flow (or DistFlow equations), which can be applied on radial distribution networks [19]. These equations can also be linearized (LinDistFlow) by assuming that power losses are negligible compared to power flows on feeders [23].

C. Equipment

Many models utilize the grid-connected distributed energy resources (DERs), such as dispatchable and non–dispatchable DG units, energy storage systems (ESS), PEV, and demand response resources (DRR). They control their active or reactive generation/consumption, so voltage regulation is achieved through power injections control. Flexible AC transmission system (FACTS) devices can also be employed for this purpose.

The conventional VVC devices, namely the on-load tap-changer (OLTC) of the transformer in HV/MV substation, step voltage regulators (SVR), and capacitor banks (CB) are also employed by the control models. They are classified as slow-regulating devices, because their control is on a slow time-scale as opposed to the inverter-interfaced DER, which can respond much faster.

Autonomous voltage control modes can be applied to the inverters to take advantage of their regulating capabilities. A heuristic local control that originates from the control of synchronous generators and is frequently used in microgrid operation is the droop control, where normally the control of active power and reactive power regulates the frequency and voltage, respectively. With distributed control, the inverters can be controlled in a cooperative fashion and their generated power adjustments are calculated taking into account information of other nodes.

D. Variables

The reviewed models control one or more of the following variables: i) reactive power of DER, ii) active power of DER, iii) reactive compensation of CB or status of shunt capacitors (shC), iv) tap position of OLTC/SVRs, v) inverter voltage set-point, vi) DG supplied current, and vii) the set-point of FACTS devices.

E. Objectives

The primary objective of the voltage control problem is to maintain the nodal voltages within the limits. Apart from that, there are other operation criteria that are tightly connected to the voltage regulation problem. Other objectives include: i) minimization of voltage deviations on nodes, ii) optimization of voltage profile (deviation from a voltage reference value or minimization of voltage differences among nodes), iii) synchronization of voltages on buses to a voltage reference value, iv) minimization of reactive power adjustments on nodes, v) minimization of total reactive power exchange, vi) minimization in the number of switching operations, vii) maximization of DG active power output, viii) minimization of generation curtailment, ix) minimization of active power losses on feeders, and x) load/reactive power sharing.

It should be mentioned that the objective of active power sharing for frequency control will not be included in the taxonomy of the control models, since this paper comments on voltage control.

IV. Decomposition of the Voltage Control Problem

The non-linear relationship of nodal power injections and nodal voltages complicates the solution of the voltage regulation problem. Even models that adopt linearizations may prove incapable of effectively handling the fast voltage variations in large-scale networks, as it would require extensive communications to coordinate multiple components. Distributed/decentralized control schemes propose the decomposition of the voltage control problem into sub-problems in order to relax the global communication requirements.

A commonly used decomposition technique is the sensitivity analysis of the power flow equations, which provides a linearized approximation of the relationship between nodal voltages (magnitude and phase) and power injection on nodes. The classic sensitivity analysis reveals the contribution of DER to the voltage regulation. Other forms of sensitivity analysis have also been proposed, which correlate the voltage variations to tap changes [24].

Other approaches that decompose the solution and calculate the nodal voltage variation as influenced by control actions are the forward-backward sweep approach [17], [25] and the feedback approach, where electrical measurements from the PCC are used as inputs into the control algorithm (e.g., [26]). The latter can simplify the solution, as it can be independent of the grid parameters (model-free, e.g., [18]) and does not rely on power flow equations. Variants of droop control are usually employed with the feedback approach. In problems of adjusting the voltages to a reference value, dynamic equations correlate the inverter control to the global system response (e.g., [27]–[30]). In distributed optimization, dual-decomposition techniques are mostly used to decouple the original problem (see also Section V-A).

V. Methods

A. Distributed Optimization Methods

The optimal voltage control problem derives from the non-convex optimal power flow (OPF) problem. Convex relaxations such as the semi-definite programming (SDP) and second order cone programming (SOCP) have been applied, which under some conditions (e.g., radial networks) can reach the global optimum solution. The centralized convex problem is then decomposed (usually by dual-decomposition techniques) in order to be solved by distributed algorithms.

1) Consensus: In these algorithms, the control agents communicate and share among them a variable (or variables) of interest, called information state, and try to synchronize in order to reach a common state (agreement). The distributed algorithms are solved iteratively until they reach the global optimum, which, in this case, is the vector of the decision variables that will optimize the cost function of the problem.

Simple consensus algorithms have been applied in [9], [10], [31], and [32]. In [9], a distributed optimization algorithm based on gradient ascent and the exchange of Lagrangian multipliers solves a SDP problem that optimizes active and reactive power injections and consumptions of DER and DRR. A dual-ascent method combined with a feedback strategy that updates the reactive injections at each iteration is presented in [10]. A gradient algorithm [31] minimizes the voltage differences among adjacent buses in a microgrid taking into consideration a proportional sharing of reactive injection among DGs. The attempt to implement real-time control is achieved by a distributed evolutionary algorithm in [32], where a dynamic optimization approach ensures fast convergence to near-optimal solutions even when grid conditions vary. A gossip-based algorithm [33] solves the loss minimization problem, which is approximated as a quadratic programming (QP) problem and is decoupled into an active and reactive power injection optimization problem.

In [34]–[36], the controllers are equipped with synchronized oscillators and communicate to estimate the variables that characterize the network. Distributed consensus protocols are used afterwards to determine the optimal control decision.

2) Decomposition-Coordination: The alternating direction method of multipliers (ADMM) is a method that can be applied to any convex problem, since it does not demand differentiability of the dual function. A voltage-constrained ADMM-based algorithm for reactive power control in [23] is compared with a dual-ascent algorithm, although in the comparison both algorithms are deprived of the voltage constraints. A three-phase OPF problem [37] and an alternative transformer model is proposed to optimize tap settings in unbalanced feeders and the acquired voltage reference is used by [38], where voltage deviations are minimized by reactive power control of fast regulating devices. SOCP relaxation and an ADMM algorithm with tunable parameters are employed in [39] for voltage-constrained reactive power flow optimization with the aim to minimize losses; however, simulations showed that voltage regulation at the substation was necessary to ensure operation within limits. Voltage-constrained ADMM is used in [40] and [41] as well, for the distributive solution of the SDP-relaxed OPF problem. The distributed algorithm is applied on the controllers that correspond to the partitions of an unbalanced microgrid and a LV residential network, respectively.

B. Decentralized Methods

1) Optimization Methods: Classic numerical algorithms are suggested for the solution of the multi-area problems of [11] and [42]. Each area solves the same optimization problem and the decision of its controller affects only the respective area. A linear programming (LP) problem defines the optimum generation of DG units in [11] in a network divided into subsystems by ε-decomposition. A non-linear programming (NLP) problem is solved in [42] to optimize the voltage profile by adjusting the DG set-points. A mixed-integer non-linear programming (MINLP) problem defines the optimal active and reactive set-points of flexible loads in [43] (reference [44] adds ESS to the same model). The implementation of the set-points is decided locally by the controllers of the resources to avoid saturation. A multi-agent system (MAS) with a hierarchical structure [45], [46] is implemented on a network partitioned into zones, where each zone-coordinator dispatches the active and reactive power of various DER and DRR using a gradient descent method. The power output of inverter-interfaced DERs in [47] and [48] converges to the OPF solution with the help of feedback controllers that continuously update their set-points with the transient solution. A SOCP relaxation of the OPF is proposed for reactive dispatch of the PV inverters in an attempt to minimize losses as well as energy consumption through conservation voltage reduction [49].

2) Heuristic Methods: Some works suggest heuristic methods in order to approximate the global optimum of the optimization function. In a heuristic method, there is no mathematical proof of convergence to the optimal value. The control quality that is based on heuristic solutions can only be empirically evaluated. A genetic algorithm (GA) is used in [12] and a particle swarm optimization (PSO) algorithm is used in [50] for sensitivity-based reactive power control.

Other works propose practical heuristic solutions that can be fast and easily applicable; however, they yield a sub-optimal solution to the voltage control problem. The forward-backward sweep method is used in [17] and [25] to estimate the maximum and minimum voltage on a feeder and regulate the SVR or CBs, respectively. The PV units in the model-free scheme of [18] send a distress signal in case of an overvoltage that initiates reactive power control of other PV units to avoid, if possible, active power curtailment. A practical heuristic algorithm is executed sequentially on the buses to minimize the power losses of a microgrid [22]. An 8-step algorithm seeks to minimize the voltage deviations by controlling the VR of each area in [24]. An algorithm implemented on MAS coordinates the SVR with capacitors [51]. Two MAS implemented algorithms are presented in [52], one based on Thevenin equivalent and another that utilizes a forward-backward sweep method. In [53], the PV system cooperates with the SVR to deal with ramp-rate issues and improve the power quality in their area of influence. The zone-partitioning of [54] is based on a threshold technique that dynamically adapts to the impact of each voltage regulating device. In [55], a tunable algorithm selects the control objectives (minimization of losses or voltage variations) of PV inverters.

C. Distributed Cooperation

The traditionally centralized secondary control of the microgrid is suggested to interact with the typically autonomous primary control (usually droop control). The result is a distributed cooperative secondary control scheme for voltage/frequency regulation and power sharing that substitutes local control instead of supplementing it.

1) Droop-Based: Both regular (consensus) and tracking synchronization have been applied to coordinate droop-controlled DGs. Reference [20] sets the droop parameters according to a weighted average consensus protocol, while [21] uses the same protocol to synchronize the average voltage to a reference value, while assuming varying communication topologies and time delays. A linear second-order tracking synchronization problem that uses a Lyapunov technique is proposed in [29]. The use of distributed averaging proportional integral (DAPI) controllers is introduced in [56], where the proposed controllers can be tuned to achieve different goals. In [57], consensus and tracking synchronization is used with primary and secondary control, respectively, to determine the voltage reference value that will result in proportional reactive power sharing. A distributed averaging algorithm and a tracking error synchronization algorithm are used in the voltage restoration control loop of [58] and [59], respectively. In [60], tracking synchronization is applied using a Lyapunov energy-based technique. Distributed cooperation has also been suggested for voltage regulation in DC microgrids, where droop control is applied between active power and output voltage, as in [61], or between supplied current and output voltage, as in [62], which proposes the calculation of average supplied current in order to shift voltage after droop control.

2) Droop-Free: Each controller of [27] communicates with its neighbors via a dynamic consensus protocol to estimate the average voltage and correct its estimation based on the rated voltage and the average reactive loading mismatch among its neighbors. An analogous method based on the mismatch of the currents is proposed for DC microgrids in [28].

D. Distributed Adaptive Control

Rather than adjusting to a reference value, the control system monitors its performance to self-tune its control input accordingly. The adaptive secondary voltage control is formulated as a tracking synchronization problem in [30], where neural networks are used to model the non-linear inverter dynamics.

E. Distributed Model Predictive Control

In this case, the controllers predict their future state over a finite time-horizon by interacting with their neighbors and taking into consideration their dynamics. Only the current decisions are applied and the process is repeated for the next time-step of the rolling horizon. In [63], model predictive control defines the control actions that minimize voltage deviations until the synchronization of all voltages to the reference value.

F. Decision Making

When there is a trade-off among conflicting objectives, a decision maker is employed to identify the solution. In the MAS models of [64] and [65], expert-based decision makers are incorporated in the intelligent agents, which communicate via contract net protocol (CNP), to choose the best control option. The MAS controllers of [66] exchange messages to combine their individual constraints to solve a dynamic optimal dispatch problem.

TABLE I
EVALUATION OF THE REVIEWED METHODS

Method	Evaluation
Distributed optimization (consensus)	(+) can achieve global optimum, (−) the convergence rate depends on the communication network
Distributed optimization (decomposition-coordination)	(+) can achieve global optimum, (+) can work with any convex problem, (−) the convergence rate depends on the communication network
Decentralized optimization	(+) fast computation, (−) risk of control failure in an entire area, (−) inferior transient performance
Decentralized heuristic methods	(+) practical to implement, (−) sub-optimal solutions, (−) inferior transient performance, (−) parametric changes affect the efficiency
Distributed cooperation	(+) balance between power sharing and voltage regulation, (+) scalability, (−) stability is affected by random communication delays
Distributed adaptive control	(+) robust against parametric disturbances, (−) heavy processing burden
Distributed model predictive control	(+) robust against parametric disturbances, (+) high stability, (−) heavy processing burden
Decision making	(+) suitable for conflicting objectives, (−) sensitive to incorrect data or data sequence
Hybrid methods	(+) fewer convergence issues, (−) no guarantee of optimality

(+): advantages, (−): shortcomings.

G. Hybrid Methods

In these methods, distributed control is initiated for DER sharing only when local control fails to keep voltage within limits. The hybrid schemes of [26], [67], and [68] use consensus algorithms for distributed control of ESS, while [69] shares active curtailment of PV units. In [70], the local controllers request additional reactive support from their neighbors via a distributed algorithm.

H. Evaluation of Methods

Although distributed optimization schemes are flexible and robust and utilize the minimum flow of information to achieve coordination and calculate the value of cost function, they can suffer from a slow convergence rate. Their performance depends on the choice of the distributed algorithm although the most critical is the choice of the communication network. Heuristic approaches are practical to implement and can deal with convergence issues, however, they offer sub-optimal solutions leading to lower quality of voltage control and often inferior transient performance. Distributed optimization has the potential to reach the global optimum under certain assumptions, thus achieving nearly the same control quality of centralized schemes.

Another important issue regarding the performance of the optimization methods is whether the set-points are applied at each iteration or only after the control algorithm converges. In distributed cooperation, feedback controllers provide continuous input to the algorithms and dynamically adjust the inverter outputs to control the voltage at the PCC. This approach has been also applied in [10], [47], and [48] (that also utilize feedback strategies), as well as in [32] and [33]. The iterative implementation of the transient solution is particularly challenging, because it has to be constraint-feasible at each update. Furthermore, the transient set-points

TABLE II
TAXONOMY OF THE REVIEWED PAPERS

Reference	Coordination Scheme	Variables	Objectives	DSM	Decomposition Techniques	Solution Methodology
[9]	Distributed	Active and reactive power of DER and DRR	Min. of power losses	AC-BIM	Dual-decomposition	Distributed optimization (simple consensus)
[10]	Distributed	Reactive power of DG	Min. of power losses	AC-BIM	Dual-decomposition	Distributed optimization (simple consensus)
[11]	Decentralized (multi-area)	Active and reactive power of DG	Min. of reactive deviations and max. of active output	AC-BIM	ε-decomposition of sensitivity matrix	Decentralized solution (optimization)
[12]	Decentralized (multi-area)	Reactive power of DRR, OLTC	Min. of reactive power and voltage deviations	AC-BIM	ε-decomposition of sensitivity matrix	Decentralized solution (heuristic)
[17]	Decentralized	OLTC/SVR	Satisfaction of voltage limits	AC-BIM	Forward-backward sweep approach	Decentralized solution (heuristic)
[18]	Local and decentralized	Active and reactive power of DG	Satisfaction of voltage limits	AC-BIM	Feedback approach	Decentralized solution (heuristic)
[20]	Local and distributed	Reactive power of DG	Satisfaction of voltage limits and power sharing	AC-BIM	Feedback approach	Droop-based distributed cooperation
[21]	Local and distributed	DG active and reactive power, inverter voltage set-point	Synchronization to voltage reference and power sharing	AC-BIM	Feedback approach	Droop-based distributed cooperation
[22]	Decentralized	Active power of DG, PEV	Min. of power losses	AC-BIM	Sensitivity analysis	Decentralized solution (heuristic)
[23]	Distributed	Reactive power of DG	Min. of power losses	DistFlow	Dual-decomposition	Decomposition-coordination
[24]	Decentralized	Tap position of OLTC	Min. of voltage deviations	AC-BIM	Sensitivity analysis	Decentralized solution (heuristic)
[25]	Decentralized	CB	Min. of voltage differences among buses	AC-BIM	Forward-backward sweep approach	Decentralized solution (heuristic)
[26]	Local and distributed	Active power of ESS and DG, reactive power of DG	Satisfaction of voltage limits	AC-BIM	Feedback approach	Hybrid
[27]	Distributed	Reactive power of DG, inverter voltage set-point	Satisfaction of voltage limits and power sharing	AC-BIM	Feedback approach	Droop-free distributed cooperation
[28]	Distributed	DG supplied current, inverter voltage set-point	Satisfaction of voltage limits and load sharing	DC-BIM	Feedback approach	Droop-free distributed cooperation
[29]	Distributed	Reactive power of DG, inverter voltage set-point	Synchronization to voltage reference	AC-BIM	Feedback approach	Droop-based distributed cooperation
[30]	Distributed	Reactive power of DG, inverter voltage set-point	Synchronization to voltage reference	AC-BIM	Feedback approach	Distributed adaptive control
[31]	Distributed	Reactive power of DG, CB	Min. of voltage differences among buses	AC-BIM	Feedback approach	Distributed optimization (simple consensus)
[32]	Distributed	Reactive power of DG, DRR	Min. of power losses	AC-BIM	ε-decomposition of admittance matrix	Distributed optimization (simple consensus)
[33]	Distributed and decentralized	Reactive power of DG	Min. of power losses	AC-BIM	Topology-based clustering	Distributed optimization (gossip)
[34]	Distributed	Reactive power of DER	Satisfaction of voltage limits	AC-BIM	Sensitivity analysis	Distributed optimization (synchronized oscillators)
[35]	Distributed	OLTC, reactive power (DG, CB, FACTS devices)	Min. (active power losses, voltage deviations, reactive power exchange)	AC-BIM	Feedback approach	Distributed optimization (synchronized oscillators)
[36]	Distributed	OLTC, reactive power (DG, CB, FACTS devices)	Min. (active power losses, voltage deviations, reactive power exchange)	AC-BIM	Sensitivity analysis	Distributed optimization (synchronized oscillators)
[37]	Distributed	OLTC	Optimization of tap settings	Unbalanced AC-BIM	Dual-decomposition	Decomposition-coordination
[38]	Distributed	Reactive power of DG, PEV	Min. of voltage deviations	DistFlow	Dual-decomposition	Decomposition-coordination
[39]	Distributed and decentralized	Active and reactive power of DG, reactive power (CB, FACTS devices)	Min. of power losses	DistFlow	Topology-based clustering	Decomposition-coordination
[40]	Distributed and decentralized	Active and reactive power of DG	Min. of power losses and cost of supplied power	Unbalanced AC-BIM	Dual-decomposition	Decomposition-coordination
[41]	Distributed and decentralized	Active and reactive power of DG	Min. (power losses, curtailment, voltage deviations)	AC-BIM	Dual-decomposition	Decomposition-coordination
[42]	Decentralized (multi-area)	Reactive power of DG	Voltage profile optimization	AC-BIM	Thevenin equivalent	Decentralized solution (optimization)
[43]	Decentralized	Active and reactive power of DRR	Min. (active and reactive deviations, voltage deviations)	AC-BIM	Sensitivity analysis	Decentralized optimization

(Continued)

might not be optimal and fast variations that might occur before the convergence to the final solution could lead to an oscillatory behavior. In general, this approach couples the behavior of the control algorithm with the convergence rate of the optimization procedure. On the other hand, it can, in some cases, adapt to variations in a more efficient way.

TABLE II
(CONTINUED)

[44]	Decentralized	Active and reactive power of ESS	Min. (active and reactive deviations, voltage deviations)	AC-BIM	Sensitivity analysis	Decentralized optimization
[45], [46]	Decentralized (multi-area)	Active and reactive power of DER, DRR	Min. cost of active and reactive adjustments	AC-BIM	Sensitivity analysis	Decentralized optimization
[47]	Decentralized	Active and reactive power of DER	Min. (reactive deviations, curtailment)	AC-BIM	Feedback approach	Decentralized optimization
[48]	Decentralized	Active and reactive power of DG	Min. (reactive deviations, curtailment, cost of supplied power)	AC-BIM	Feedback approach	Decentralized optimization
[49]	Decentralized	Reactive power of DG, shC	Min. (power and inverter losses, energy consumption)	DistFlow	Dual-decomposition	Decentralized optimization
[50]	Decentralized (multi-area)	Reactive power of DG	Min. of power losses	AC-BIM	Sensitivity analysis	Decentralized solution (heuristic)
[51]	Decentralized (multi-area)	SVR, CB	Min. power losses and switching operations	AC-BIM	Forward-backward sweep approach	Decentralized solution (heuristic)
[52]	Decentralized (multi-area)	Active and reactive power of ESS	Min. (voltage deviations, state of charge adjustments)	AC-BIM	Sensitivity analysis	Decentralized solution (heuristic)
[53]	Decentralized (multi-area)	Active and reactive power of DER, SVR, CB	Voltage profile improvement	AC-BIM	Sensitivity analysis	Decentralized solution (heuristic)
[54]	Decentralized (multi-area)	Reactive power of DG	Voltage profile improvement	AC-BIM	Sensitivity analysis	Decentralized solution (heuristic)
[55]	Decentralized	Reactive power of DG	Min. of power losses or min. of voltage deviations	DistFlow	Feedback approach	Decentralized solution (heuristic)
[56]	Local and distributed	Reactive power of DG	Satisfaction of voltage limits and power sharing	AC-BIM	Feedback approach	Droop-based distributed cooperation
[57]	Distributed	Reactive power of DG, inverter voltage set-point	Satisfaction of voltage limits and power sharing	AC-BIM	Feedback approach	Droop-based distributed cooperation
[58]	Distributed	Active and reactive power of DG, inverter voltage set-point	Synchronization to voltage reference	AC-BIM	Feedback approach	Droop-based distributed cooperation
[59]	Distributed	Reactive power of DG, inverter voltage set-point	Synchronization to voltage reference	AC-BIM	Feedback approach	Droop-based distributed cooperation
[60]	Distributed	Reactive power of DG, inverter voltage set-point	Synchronization to voltage reference	AC-BIM	Feedback approach	Droop-based distributed cooperation
[61]	Distributed	Active power of DG	Voltage profile improvement	DC-BIM	Feedback approach	Droop-based distributed cooperation
[62]	Distributed	DG supplied current, inverter voltage set-point	Satisfaction of voltage limits and load sharing	DC-BIM	Feedback approach	Droop-based distributed cooperation
[63]	Distributed	Reactive power of DG	Synchronization to voltage reference	AC-BIM	Feedback approach	Distributed model predictive control
[64]	Decentralized	OLTC, CB, active and reactive power of DG	Min. (voltage deviations, switching operations, reactive power injection, curtailment)	DistFlow	Sensitivity analysis	Decision making
[65]	Decentralized	OLTC , active and reactive power of DG,	Min. (voltage deviations, tap operations, curtailment, reactive adjustments)	DistFlow	Sensitivity analysis	Decision making
[66]	Decentralized	Active and reactive power of DER	Satisfaction of voltage limits	AC-BIM	Sensitivity analysis	Decision making
[67]	Local and distributed	Active power of ESS, reactive power of DG	Satisfaction of voltage limits	AC-BIM	Feedback approach	Hybrid
[68]	Local and distributed	Reactive power of ESS, DG, active power of ESS	Satisfaction of voltage limits	AC-BIM	Sensitivity analysis	Hybrid
[69]	Distributed	Active power of DG	Satisfaction of voltage limits	AC-BIM	Sensitivity analysis	Hybrid
[70]	Local and distributed	Reactive power of DG, PEV	Satisfaction of voltage limits	AC-BIM	Sensitivity analysis	Hybrid

Table I summarizes the advantages and shortcomings of the reviewed methods.

I. Taxonomy of Reviewed Works

Table II presents the taxonomy for each of the reviewed papers for quick reference.

VI. FUTURE RESEARCH

A. DER Participation

It is important to examine which regulations will accommodate the ancillary services provided by DER owners. Although the revised IEEE 1547 Standard for interconnection of DER [71] has allowed the voltage regulation by DG by means of changing their active and reactive power, the "plug and play" policy has not been promoted yet and most DGs operate at a fixed (unitary) power factor mode. In order to take full advantage of the distributed reactive power loading/generation capabilities and increase the flexibility of the grid operation, further revisions are required to define the specifications of Volt/Var control. More importantly, there is a need to allow the interoperability of dissimilar network components in order to implement distributed control.

B. Demand Side Management

It is expected that consumers will have an active role in the energy management and operation of the future smart grid. The employment of demand-side resources, such as PEV and other controllable loads, can make up for the generation variability and increase power quality. Demand-response under the scope of distributed voltage control and the engagement of end-users in voltage regulation should be further explored.

C. Energy Market

Aside from the technical aspects, it is also important that the planning of the future energy market should examine the conflicting interests of the stakeholders and enable mutual benefits from the voltage regulation for distribution system operator (DSO) and independent producers. The engagement of end-users should also be supported by compensation or other incentives.

D. ICT Integration

The smart grid should provide all the necessary digital technologies that would assist the communication among all participants whether those are deployed at the supply-side or the demand-side. As distributed control is much less restricted by the limited bandwidth, it could be supported by the low-cost power line communication (PLC), which exploits the already available infrastructure of the electricity network. Perhaps a combination of both wired and wireless communications would be a cost-effective solution that could also provide reliability and robustness against measurement noise and communication delays. One of the biggest challenges would be to accomplish a significant increase in data refresh rate. Thus, the controllers could frequently acquire all the measurements or other information (e.g., from neighboring buses) that are necessary for their coordination and respond to any imbalance between generation and demand.

E. Data Privacy and Security

The limited exchange of information in distributed control will strengthen the data security and protection of consumers' privacy. However, it is suggested to investigate the resiliency of distributed control architecture against cyber-attacks, as its effectiveness against false data injection attacks is unclear.

VII. Industry Perspectives

Despite the recent advances in ICT, it is challenging to envision and design an industrial distributed control infrastructure for large-scale implementation in distribution networks. Up until now, the power system control has been centralized and inflexible and has been performed by the transmission system operator (TSO) in cooperation with the DSO [72]. In the distribution system, in particular, directly controlling each device is too complicated, as the DSO would have to know the various technical details of multiple heterogeneous DER, which is hard to achieve at LV level, where small-scale DG owners and consumers could participate in the regulation.

Decentralized control schemes have already gathered some attention and various small-scale applications have been deployed in field sites. For example, the tests on Kythnos island (the first MAS implementation for decentralized DER dispatch) proved successful having although the drawback that such an infrastructure is too expensive for a small group of DER owners [73]. Although promising results exist and novel ICT developments (such as the technology of Grid computing [74]) lead the path to more decentralized structures, industry exhibits innate inertia to invest in innovative solutions that have a different philosophy. In addition, it is mandatory to raise social awareness in energy matters in order to deploy such novel technologies, since the participation of grid customers and small-scale producers is a prerequisite. Therefore, there is a great need for more pilot sites and large-scale tests.

A decentralized architecture, which could be realized by assigning parts (zones) of the distribution network to different zone coordinators, seems more reasonable to be implemented as a first step, since it could still maintain a level of hierarchy. The DSO would only need to provide instructions according to his targets without entering into details of how these systems will internally handle the instructions. Thus, decentralized voltage regulation could be organized among a group of DER owners represented by an aggregator and provided as ancillary services at the level of distribution.

VIII. Conclusion

In this paper, the state-of-the-art publications on distributed and decentralized voltage control are reviewed and classified. The definitions of the different coordination schemes are introduced along with their classification based on communication. The control models include the controllable components, the coordination among them, the control variables and the objectives. The solution methodologies are discussed starting from the decomposition of the initial problem. The taxonomy table, which presents both the control models and the solution methodologies that were developed, serves as a guide and gives insight to recent research and the direction it has followed over the past few years. Moreover, the methods are evaluated to highlight their advantages and shortcomings. This paper also identifies areas of future research and comments upon the industry perspectives of distributed control implementation.

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