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DOI:
10.1109/PowerTech55446.2023.10202910

Document status and date:
Published: 09/08/2023

Document Version:
Accepted manuscript including changes made at the peer-review stage

Review of Recent Developments in Technical Control Approaches for Voltage and Congestion Management in Distribution Networks

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***Abstract*—The increasing installation of distributed energy resources in residential households is causing frequent voltage and congestion issues in low- and medium-voltage electrical networks. To defer or avoid the costly and complicated grid expansion, technical, pricing-based, and market-based approaches have been proposed in the literature. These approaches can help distribution system operators (DSOs) exploit flexible resources to manage their grids. This study focuses on technical control approaches, which are easier to implement, and provides an up-to-date review of their developments in modeling, solution approaches, and innovative applications facilitating indirect control from DSOs. Challenges and future research directions are also discussed.**

***Index Terms*—Voltage control, congestion management, online feedback optimization, operating envelopes, capacity limits**

I. Introduction

Distributed energy resources (DERs) are being installed in residential households as part of carbon-neutrality goals. However, this is leading to congestion issues for grid assets, which can result in their aging and damage, and significant voltage deviations, especially for distribution networks with a high resistance/reactance (R/X) ratio [1], [2]. The traditional approach to addressing these issues is grid expansion. This requires significant investments, but more problematic are the long time and shortage of staff available to implement it [3].

To help distribution system operators (DSOs) manage voltage and congestion issues, various approaches have been proposed, including technical, pricing-based, and market-based solutions [4]. Technical approaches involve coordinators such as DSOs or aggregators dispatching controllable assets, often by solving optimal power flow problems while taking grid limits into account. In contrast, dynamic pricing schemes impact the consumption patterns of end-users, assuming they are cost-responsive. Such schemes include transactive energy (TE) [5], [6], distribution locational marginal pricing (DLMP) [7], [8], etc. Local energy/flexibility markets are used in market-based approaches, where DERs are (re-)dispatched based on market signals under local grid limits. Although promising simulation results have been reported, pricing and market-based schemes face several challenges, such as price insensitivity, lack of liquidity, and baselining [9]. This paper thus focuses on technical control approaches, as they have lower implementation complexity, and provides an up-to-date review of their developments in modeling, solution approaches, and innovative applications that facilitate indirect control from DSOs.

The literature contains several reviews that are relevant. For example, an overview of models for market-based and technical approaches is presented in [4]. However, this review does not delve into the complexities of active and reactive power control or cover their recent developments. References [1], [2] focus specifically on voltage control, identifying different communication and control architectures. While [1] presents challenges for local volt/var control (VVC), [2] reviews methodologies for distributed and decentralized voltage control in smart distribution networks.

In [10]–[12], attention is given to decentralized and distributed optimization. With modeling details of various techniques presented in [10], their applications to several power system problems are reviewed in [10], [11]. A further classification of decentralized and distributed techniques used for distribution network control based on data exchange mechanisms, implementation, models, communications, algorithms, and applications was conducted in [12]. Given the rich literature on decentralized and distributed optimization, we review only their advances in an important class: mixed-integer problems. Likewise, we refer to [13] for a recent extensive review on generation and load uncertainty handling.

Additionally, we review recent developments of a promising technique: online feedback optimization (OFO). Other than offline approaches (centralized, decentralized, distributed) where decisions are not implementable until convergence (i.e. power flow relations might not be satisfied for the intermediate solutions), OFO produces meaningful intermediate iterates where power flow relations are enforced by physical grids.

This project is funded by TKI Energie from the *Toeslag voor Topconsortia voor Kennis en Innovatie (TKI)* from the Ministry of Economic Affairs and Climate under reference 1821401.

Moreover, OFO enables real-time operations, avoids pervasive load metering, works with the dynamics of loads and renewables, and can cope with model inaccuracy due to its feedback nature [14]. These characteristics render it rather applicable to distribution network management. While [15] presents a use case elaborating the principle of a particular realization, [10] reviews its applications in real-time optimal power flow, frequency and voltage control. Compared to [10], we focus on distribution grids and provide a more up-to-date review. Moreover, we present an overview of literatures leveraging OFO for distribution grid management.

The main contribution of this paper is that we provide an up-to-date review of recent advances in technical approaches applicable to voltage and congestion management in distribution networks, covering new concepts and topics in model developments, solution methodologies, and applications facilitating indirect DSO control. Challenges and future research needs are discussed. This review paper aims to promote and advance techniques for distribution network management.

The remainder of this paper is organized as follows: Section II presents the fundamentals of optimal power flow control and several communication architectures. Sections III to V review the recent developments of technical control in modeling, solution approaches, and innovative applications respectively. Finally, conclusions are drawn in Section VI.

II. Preliminaries

A. OPF Models

As one of the most important problems in power systems, optimal power flow (hereinafter OPF) pursues a certain objective subject to power flow relations, grid and asset limits. The problem is flexible in its formulations. Typical objective functions include minimization of power losses, voltage deviation to reference, generation curtailment, load shedding, reactive power compensation, the number of switching operations, and a combination of those. Decision variables represent for instance transformer tap positions, capacitor bank settings, and active/reactive power of DERs including HVAC units, electric vehicles, battery storage, and photovoltaics (PVs). OPF can be solved in multiple stages and in different time scales based on the reaction speeds of primary control devices. For instance, the operation of mechanical slow-regulating on-load tap changers (OLTCs) and capacitor banks (CBs) is determined before that of inverter-based fast-reacting DERs, which can be re-scheduled in real time [16], [17].

The main complexity of OPF arises from the nonlinear and non-convex power flow relations. To this end, nonlinear programming (NLP) formulations, convex relaxations e.g. second-order cone programming (SOCP) and semidefinite programming (SDP) formulations, and linear approximations have been proposed and are lately reviewed in [10], [15]. Further classifications of those formulations can be based on the usage of the bus injection model (BIM) or branch flow model (BFM), rectangular or polar forms, and generalizability to multi-phase unbalanced grids. Recent work in [18] has visualized and presented simulation results for various formulations. While

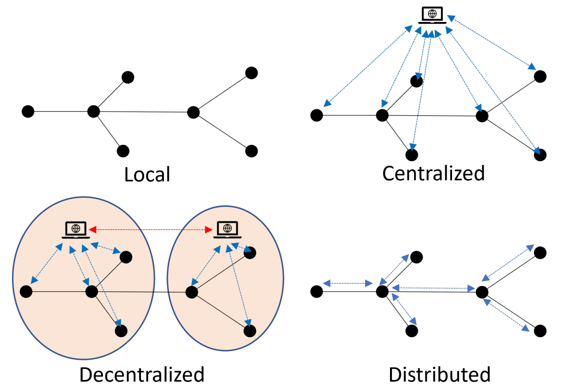

Fig. 1. Communication architectures: solid black lines represent physical connections, while blue dotted arrows represent communication directions.

the BFM is seen as more suitable for radial distribution feeders [18], a proper choice has to be made considering problem size, objective function, accuracy requirement, etc.

B. Communication Architectures

Throughout this paper, communication architectures of various algorithms will be considered. We clarify these architectures herein, see also [2] and Fig. 1. In *local* control e.g. droop-based volt/var control, control signals are computed with only local information. The solution optimality is generally compromised to relieve communication burdens. In *centralized* control, local information is sent to a central agent, which carries out centralized computation and provides control signals to each node. While communication can be challenging, this paradigm usually can achieve globally optimal solutions assuming perfect information. In *decentralized* control, the network is partitioned into different control zones. In each zone, a local agent acts like a central agent. Information exchange is allowed between those local agents. Finally, in *distributed* control, information is exchanged only between physically connected neighboring nodes.

In the following three sections, we review respectively recent developments of technical control approaches in modeling, solution approaches, and innovative applications facilitating indirect control from DSOs. A summary of these developments is presented in Fig. 2.

III. Model Developments

A. Physically Realizable Solutions

In this section, we review several recent additions to OPF. One stream of research aims to bring *physically realizable* solutions to OPF. As convex relaxations or linear approximations are often used, grid states such as bus voltages and line loadings are usually inaccurately represented [18]. For instance, the widely used *DistFlow* model [19] generally requires the objective function to be monotonically increasing with line currents, which is not applicable to many practical problems. When the optimized decisions are implemented in

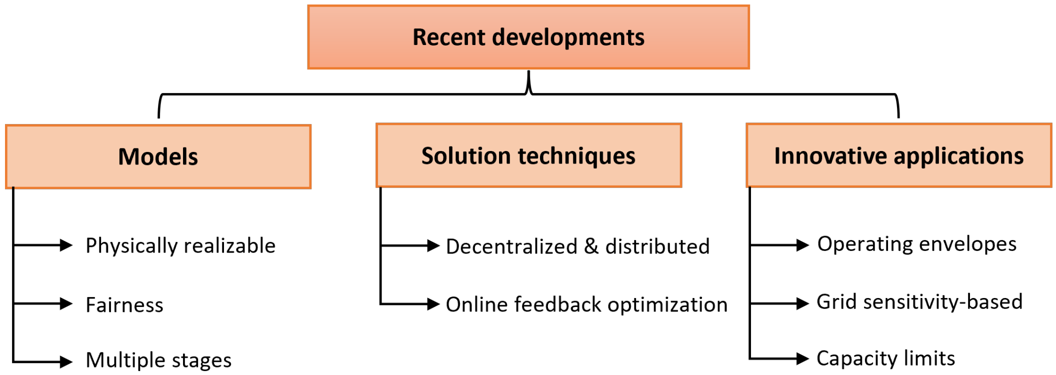

Fig. 2. Classification of recent developments in technical control approaches for voltage and congestion management in distribution networks.

actual grids, voltage and loading limits might be violated, which is known as *AC-infeasibility*.

To this end, [20] proposed to increase the weight of a loss minimization term in a multi-objective formulation until the relaxed power flow constraint is binding hence an *AC-feasible* solution is obtained. On the other hand, [16], [21] suggested a convex inner approximation, which is built on an exact linear relation between bus voltages with nodal injections and current flow (11b, [16]). By bounding the current flow term from below and above, linear constraints are formulated and added to the OPF ensuring the voltage limits are kept with optimized nodal power injections. To address the complexity of a multi-period NLP formulation for energy storage dispatch, [22] proposed to first solve its relaxed SOCP problem. By fixing active power setpoints as determined from the relaxed problem, the original NLP formulation is decoupled over time steps and can be solved per time step with less complexity to optimize reactive power. The obtained active and reactive power setpoints then satisfy the nonlinear power flow relations.

In [23], attention is given to battery storage. Due to the non-concurrent nature of charge and discharge, a complementarity constraint, i.e. $p^{ch}p^{dis} = 0$ where p^{ch} and p^{dis} represent the battery charge and discharge respectively is incorporated [24]. To linearize this constraint, a binary variable δ is introduced, formulating a mixed-integer programming (MIP) problem, i.e. $0 \leq p^{ch} \leq M\delta, 0 \leq p^{dis} \leq M(1-\delta)$, where M is a sufficiently large number. However, MIP formulations can be computationally expensive, particularly when dealing with numerous batteries or multiple time steps. By dropping the complementarity constraint and taking the net battery power exchange for implementation, i.e. $p^{net} \leftarrow p^{ch} - p^{dis}$, the model convexity is restored. However, this procedure underestimates the battery state of charge (SoC) due to charge and discharge losses, resulting in possible violations of the upper SoC limit. As the resulting SoC trajectory might not respect the actual SoC limit, the charge and discharge plan is seen as *physically unrealizable*. In this regard, [23] proposed a new linear battery model (15b-15f, [23]), providing lower and upper bounds on the battery SoC. The model ensures that the obtained charge/discharge plan will not violate the actual SoC limits.

As pointed out in [24], the proposed model in [23] cannot impose final energy targets. It might cut off feasible solutions and flag infeasibility when at least one feasible solution exists. The simulation results in [25] have also raised concerns about the accuracy of the model. Given the modeling simplicity and linearity (i.e. scalability) of this model, further research is needed to evaluate its applicability and address these issues.

B. Fairness

As remuneration schemes are currently not in place for end-users in LV grids, fairness is an important consideration for the successful implementation of strategies such as active power control. Fairness refers to fairly distribute benefits, burdens, or costs among different end-users [26], which is especially relevant in the case of active power curtailment from PVs supporting grids for voltage control. End-users located at the far end of distributed feeders typically experience more frequent voltage limit violations. Without fairness considerations, substantial active power curtailment is incurred to them. To this end, [27] proposed three different fairness notions and developed OPF models to ensure fairness among end-users under these three notions. While fairness is ensured and grid limits are kept, the models (similarly the ones in [28]–[30]) can result in a significant amount of unnecessary curtailment to achieve fairness due to the use of strict equality fairness constraints, e.g. enforcing the same proportion of curtailment under the proportional fairness formulations [27]. Alternatively, quadratic [31], [32], min-max [33], [34], and logarithmic [35] objective function are designed to mitigate unfairness while avoiding unnecessary curtailment. Using these objective functions, fairness is slightly compromised for energy harvest. Choices of the model to use should be made based on local policies and the willingness of end-users. Moreover, fairness for active power control of load units is not as straightforward as generation curtailment, especially for those with intertemporal relations. Clear definitions and models should be developed in future work.

C. Multiple Stages

Due to the separation in the time scale different assets work at, OPF problems can be solved in multiple stages to derive

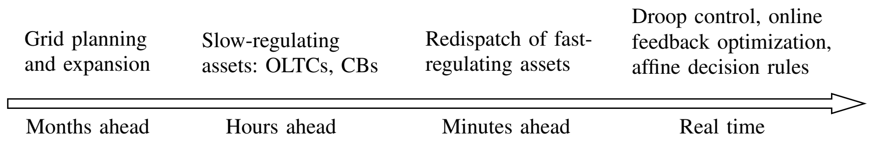

Fig. 3. Stages of distribution grid management: from planning to real time.

control decisions for assets with different regulating speeds. For instance, slow-regulating legacy grid assets such as OLTCs and CBs do not respond as fast as inverter-based assets such as PVs and cannot be controlled as frequently due to practical lifetime considerations. Therefore, they are usually optimized hours ahead and are static in real time when fast inverter-based assets are in place to track variations in generation and loads. Figure 3 summarizes four stages for distribution grid management, spanning from grid planning to real-time control, divided according to the time scale.

In [16], [36], the coordination between hourly-scheduled OLTCs and CBs and minutely-dispatched reactive power from PV inverters for voltage control was studied. References [37], [38] extended this coordination to include real-time control, by coordinating minutely reactive power setpoints and real-time volt-var droop control parameters of PV inverters using linear and general droop functions respectively. The recently developed OFO was applied in [17] to compensate for the inadequacy of OLTCs for voltage control in real time. In [39], [40], the affine decision rules, which simulate real-time recourse decisions when uncertainties of generation and loads are revealed, were coordinated with generation curtailment and OLTCs respectively. Finally, [41] studied a three-stage coordination covering hourly dispatch of OLTCs and CBs, minutely reactive power dispatch, and real-time droop-based volt-var control of PVs.

While including more stages improves model accuracy and effectiveness, the modeling and computational complexity also increases significantly. Further research is necessary to develop efficient coordination models and solution methodologies.

IV. Solution Techniques

A. Decentralized and Distributed Offline Optimization

Due to the considerations of end-user privacy, risks of single-point failure, and the complexity of communication and computation of centralized optimization, decentralized and distributed approaches have received significant research attention. While [10]–[12] provide an extensive overview of algorithms applicable to continuous problem setups, we review the decomposition of MIP problems, in which discrete decision variables exist, for example, representing tap changer positions and charge/discharge states of batteries. A direct application of mathematical decomposition techniques which are developed for convex problems usually produces sub-optimal and even infeasible solutions [56].

To provide feasibility guarantees for primal variables recovered from a dual decomposition procedure, [56] proposed an additional contraction step tightening the resource vector in coupling constraints with an appropriate amount, which can be determined *a priori*. The technique was applied in [57] for the decentralized energy management of prosumers sharing a neighborhood transformer. To reduce the conservativeness of the contraction step that would otherwise decide the contraction parameter over the entire scheduling horizon, a rolling horizon control approach was proposed. In [58], a hierarchical solution methodology using branch-and-bound (B&B) was proposed. With binary variables fixed within each B&B node, classical distributed optimization algorithms (in the case of [58], generalized Benders decomposition) can be used to decompose the problem. While convergence is guaranteed, the outer-loop and inner-loop structure makes the overall algorithm computationally challenging.

B. Online Feedback Optimization (OFO)

While the offline (centralized, decentralized, distributed) optimization paradigm can achieve solution optimality with perfect feed-in information, it faces several difficulties in distribution grids. First, large-scale monitoring, measurements, and forecasts are not available in distribution grids. This can result from the high cost of installing monitoring devices or from privacy concerns of end-users. Key input parameters such as power consumption of non-controllable loads are not available or can only be roughly estimated. Second, centralized optimization requires high-quality communication of measurements and control signals, which is not yet ready for distribution networks. Moreover, as those approaches work in an open-loop fashion, communication delays and noises would undermine the optimality of solutions [43]. Finally, distribution grids are highly dynamic [46]. Traditional approaches working with an offline fashion cannot handle the distribution grid dynamics (i.e. by the time the solution is ready to implement, it may already be outdated). As a solution to those issues, OFO has recently been proposed. We explain its principle using a volt/var control problem as in (1)-(4).

$$\min_{\underline{\mathbf{q}}\leq\mathbf{q}\leq\overline{\mathbf{q}}} f(\mathbf{q}) \text{ s. t. } \underline{\mathbf{v}} \leq \mathbf{v} \leq \overline{\mathbf{v}} : \boldsymbol{\lambda}, \boldsymbol{\mu} \tag{1}$$

$$\max_{\boldsymbol{\lambda}\geq\mathbf{0},\boldsymbol{\mu}\geq\mathbf{0}} \min_{\underline{\mathbf{q}}\leq\mathbf{q}\leq\overline{\mathbf{q}}} \left\{ f(\mathbf{q}) - (\boldsymbol{\lambda}-\boldsymbol{\mu})^T\mathbf{v} + \boldsymbol{\lambda}^T\underline{\mathbf{v}} - \boldsymbol{\mu}^T\overline{\mathbf{v}} \right\} \tag{2}$$

$$\boldsymbol{\lambda}^{k+1} \leftarrow \left[\boldsymbol{\lambda}^k + \mathrm{diag}(\boldsymbol{\alpha}^k)(\underline{\mathbf{v}} - \mathbf{v}(\mathbf{q}^k))\right]^+ \tag{3}$$

$$\boldsymbol{\mu}^{k+1} \leftarrow \left[\boldsymbol{\mu}^k + \mathrm{diag}(\boldsymbol{\beta}^k)(\mathbf{v}(\mathbf{q}^k) - \overline{\mathbf{v}})\right]^+ \tag{4}$$

$$\mathbf{q}^{k+1} \leftarrow \left[\mathbf{q}^k - \mathrm{diag}(\boldsymbol{\gamma}^k)\big(\nabla f(\mathbf{q}^k) - \mathbf{X}^T(\boldsymbol{\lambda}^{k+1} - \boldsymbol{\mu}^{k+1})\big)\right]_{\underline{\mathbf{q}}^k}^{\overline{\mathbf{q}}^k} \tag{5}$$

The original optimization formulation (1) minimizes an objective function $f(\mathbf{q})$ subject to reactive power limits and

TABLE I
OVERVIEW OF STUDIES ON ONLINE FEEDBACK OPTIMIZATION FOR DISTRIBUTION NETWORK MANAGEMENT.

Reference	Control obj.[a]	Variable	Methodology	Grad. scaling[b]	DER lim.[c]	Commu.[d]	Unbalance	Imperfect information
Bolognani [42]	Voltage	Q	Dual ascent	✗	Soft	Distributed	✗	✗
Zhu [43]	Voltage	Q	GP[e]	$\mathbf{X}^{-1}$, Diagonal	Hard	Local	✓	✗
Gan [44]	Voltage	P, Q	GP	✗	Hard	Central	✓	✗
Tang [45]	Voltage, current	P, Q	Quasi-Newton	L-BFGS-B	Hard	Central	✗	✗
Dall'Anese [46]	Voltage	P, Q	Primal-dual GP	✗	Hard	Central	✗	✗
Liu [47]	Voltage	Q	ADMM	✗	Hard	Distributed	✓	Commu.
Bernstein [14]	Voltage, current	P, Q	Primal-dual GP	✗	Hard	Central	✓	Measure.[f], commu., model.[g]
Liu [48]	Voltage	Q	Partial primal-dual GP	$\mathbf{X}^{-1}$	Hard	Hybrid	✓	Commu.
Qu [49]	Voltage	Q	Primal-dual GP	$\mathbf{X}^{-1}$	Hard	Distributed	✓	Measure., commu., model.
Magnússon [50]	Voltage	P, Q	Dual ascent	✗	Hard	Distributed	✗	Measure., commu., model.
Picallo [51]	Voltage	P, Q	GP	✗	Hard	Central	✓	Measure.
Ortmann [52]	Voltage	Q	Dual ascent	✗	Hard	Central	✗	Model.
Tang [17]	Voltage	Q	Dual ascent	$\mathbf{X}^{-1}$	Soft	Distributed	✗	✗
Ipach [53]	Voltage, current	P, Q	Primal-dual GP	✗	Hard	Central	✗	Commu.
Cheng [54]	Voltage	Q	GP	Inv Hessian approx.[h]	Hard	Central	✓	✗
Patari [15]	Voltage	P, Q	Dual ascent	✗	Hard	Distributed	✓	Measure., commu., model.
Ipach [55]	Voltage, current	P, Q	Primal-dual GP	✗	Hard	Distributed	✓	Commu.

[a]Control objective, [b]Gradient scaling, [c]DER limit, [d]Communication, [e]Gradient projection, [f]Measurement, [g]Modeling, [h]Inverse Hessian approximation

nodal voltage limits. $\mathbf{v}$ is the nodal voltage vector. $\mathbf{q}$ represents nodal reactive power injection. $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ are respective dual variables. The other terms represent their respective limits. We leverage a linearized voltage formulation $\mathbf{v}(\mathbf{q}) = \mathbf{X}\mathbf{q} + \mathbf{v}_0$, where $\mathbf{X}$ and $\mathbf{v}_0$ can be determined from [16], [43], [59]. We further leverage a primal-dual gradient projection (PDGP) algorithm as in [14], [46] to solve its equivalent dual formulation in (2). The algorithm consists of two dual GP steps in (3) and (4), where $[\cdot]_{\underline{\mathbf{q}}^k}^{\overline{\mathbf{q}}^k}$ and $[\cdot]^+$ denote respectively componentwise projections into the box constraint $[\underline{\mathbf{q}}^k, \overline{\mathbf{q}}^k]$ and the nonnegative orthant, and a primal GP step in (5). The diagonal matrices represent respective step lengths, which can vary over end-users. Theoretical results tend to provide conservative step lengths to guarantee some contraction property of the algorithm, which is key to its convergence analysis [49]. For this reason, numerical tests are important to choose satisfactory step length parameters.

Furthermore, by replacing $\mathbf{v}(\mathbf{q}^k)$ with instantaneous voltage measurements $\tilde{\mathbf{v}}^k$ in (3) and (4), the algorithm works in a closed-loop fashion. This allows it to cope with modeling errors and communication degradation [52], [55]. Although the dual GP steps (3) and (4) can be carried out locally based on local voltage measurements, the primal GP step (5) requires communication of $\boldsymbol{\lambda}^k$ and $\boldsymbol{\mu}^k$ due to the non-sparsity of $\mathbf{X}$. Compared to its offline counterpart, OFO 1) does not require data of non-controllable loads, 2) has lighter communication and privacy issues since only $\boldsymbol{\lambda}^k$ and $\boldsymbol{\mu}^k$ are communicated which concern only nodal voltage information, 3) works in a closed-loop fashion, and 4) is carried out in an online manner with update steps involving only simple calculations.

In Table I, we provide an overview of recent studies employing OFO for distribution grid management. We classify these studies based on 1) objectives: voltage or current management, 2) variables: active or reactive power, 3) underlying methodologies, 4) gradient scaling which is used to accelerate the convergence or to facilitate distributed communication, 5) handling of DER limits which can be treated as soft or hard constraints, 6) communication structures of dual information, 7) handling of phase unbalance, and 8) considerations of measurement errors, communication degradation, and grid modeling errors. This provides an overview and a quick reference of existing works and is dedicated to promoting future advances of OFO as a promising technical approach for real-time distribution grid management.

V. APPLICATIONS FACILITATING INDIRECT CONTROL

In contrast to several methods in the previous sections which assume that DSOs can directly dispatch DERs owned by end-users, recent studies have discussed decoupling DSOs from such a central role out of regulation and privacy considerations. Three promising concepts are reviewed in this section.

A. Operating Envelopes

In [32], [35], [60]–[62], a novel concept of *operating envelopes* was proposed and developed, which are defined as *time-varying meter-level export/import limits that a distribution company issues to aggregators as a practical way to ensure network integrity while facilitating residential DER services* [60]. End-users follow these limits to operate their DERs, while DSOs only need to compute and publish these limits. This clarifies the role of DSOs in managing grid assets without engaging in control of residential DERs and is aligned with the DSO unbundling requirements. Looking into how operating envelopes are computed, OPF with explicit grid constraints and objective functions of import/export limit maximization is the backbone. Grid topology and forecasts of generation and loads at least for passive end-users are required. Fairness was imposed with quadratic [32], logarithmic [35], and max-min [62] objective functions. To counter uncertainties with day-ahead generation and load forecasts, a chance-constrained formulation assuming forecast errors are addressed with residential batteries leveraging affine decision rules was proposed in [62]. While [32], [35], [60], [62] are only concerned with active power limits, [61] proposed the *PQ Operating Envelope* as the intersection of voltage safe operating region (VSOR) and current safe operating region (CSOR). Finally, electrical model-free operating envelopes can be developed leveraging neural networks for voltage calculations [63].

We note that the under- or unbalanced utilization of these import/export limits can create voltage issues, especially in severely unbalanced grids or when OLTCs are leveraged to create voltage headroom/legroom [60]. Extensive simulation or incentive development for end-users to fully or evenly use these limits is seen as important to address this concern.

B. Grid sensitivity-based Control

While DSOs publish limits towards active end-users in the above scheme, in [64], DSOs perform grid monitoring and publish network states and sensitivities concerning voltages and currents. Aggregators incorporate those network states and sensitivities as additional constraints in their portfolio optimization problems, which ensures distribution network integrity and the quality of their electricity services.

C. Capacity Limits

The last reviewed grid managing tool concerns capacity limits (CLs) [9], [65], [66], which, unlike operating envelopes, are procured by DSOs over a longer period (e.g. a month ahead). Aggregators offer DSOs CL services which put restrictions on their consumption below specific limits. In contrast to transmission systems where power balance and thus frequency is concerned, DSOs' main concerns are voltage and congestion issues. Thus motivating aggregators to closely follow a schedule is less attractive than putting a limit on their consumption [9]. Reference [65] presents a methodology to forecast an aggregator's opportunity cost of providing a CL service, which can be later used to construct bidding curves in CL service markets cleared by DSOs to manage their grid issues. In [66], the impact of different CL service levels and service areas on network states was probabilistically assessed, which can assist DSOs to select adequate and cost-effective CL services. It remains unclear and challenging how DSOs can choose potentially a combination of CL services from the market other than using a brute force method reported in [66]. Moreover, static limits are challenged by the dynamic nature of non-controllable loads. Highly restrictive CLs are likely to be requested to ensure network safety, which significantly (exponentially [65]) increases the opportunity costs of aggregators and thus the costs of DSOs purchasing these CL services. Time-varying CL services respecting distribution system dynamics can be a promising option.

VI. Conclusions

This paper reviews recent advances in technical control approaches developed for voltage and congestion management in distribution networks. These are classified into model developments, solution methodologies, and innovation applications facilitating indirect DSO control. Throughout this paper, important challenges and future research needs are discussed.

Considering also market-based and dynamic pricing-based methods, rich approaches exist for distribution grid management. An important question to address is how these approaches can be integrated. In this paper, the multi-stage coordination is discussed, where approaches working at different time scales can be combined. One can also think about the issues targeted. For instance, capacity limits can be procured monthly to address transformer congestion, while OFO can be leveraged to address fast voltage deviations. Looking into the devices, OFO cannot explicitly consider the energy requests of electric vehicle users. Combining OFO with offline multi-period optimization is then promising for grid-supporting electric vehicle management. Given the rich approaches and possibilities, it is recommended in future works to advance the integration of different approaches.

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