IEEE POWER & ENERGY SOCIETY SECTION

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 14, 2021, accepted December 31, 2021, date of publication January 7, 2022, date of current version March 18, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3141235

Reactive Power Markets: A Review

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This work was supported in part by the German Federal Ministry of Education and Research through the Project PYRATE under Grant 01IS19021A, in part by the Lower Saxony Ministry of Science and Culture within the Lower Saxony "Vorab" of the Volkswagen Foundation under Grant 11-76251-13-3/19–ZN3488 (ZLE), and in part by the Center for Digital Innovation (ZDIN).

ABSTRACT Liberalization of the energy system sets the way towards market-based solutions for ancillary service provision. Local reactive power markets are envisioned to achieve more economically and technically efficient reactive power provision to solve voltage control problems in future distribution and transmission grids. However, market-based reactive power procurement is a difficult and yet unsolved problem. This survey provides a comprehensive overview of the characteristics and hardships of reactive power markets. That is followed by a literature overview of reactive power market design, including local markets and markets on system operator level. Further, methods how to analyse reactive power markets are discussed, focusing on market power, game theoretical approaches, Reinforcement Learning, and manipulation of reactive power markets. From this overview, trends and current research gaps are derived and some general research recommendations are given to serve as a guideline for future research in the field of reactive power markets.

INDEX TERMS Ancillary service, game theory, market design, market power, mechanism design, reactive power market, reinforcement learning, system service, voltage control, voltage regulation.

I. INTRODUCTION

Reactive power regulation is the main measure to perform voltage control in power grids. Reactive power itself does not bring direct benefits, but increases the active power transfer capability of the system and decreases active power losses, if regulated well [1].

The current transformation of the energy system towards renewable energy sources results in some general trends, which change the role of reactive power. While conventional power plants in the transmission system get shut down, the penetration of power grids with distributed energy resources (DERs) increases steadily, especially in the distribution grids. Especially fluctuating DERs like most renewables often can induce voltage violations and overloading. Therefore, grid expansion measures and better control mechanisms are required. In future power systems, DERs in distribution systems will be the main providers for ancillary services like voltage control. Especially converter-connected DERs like photovoltaic (PV) systems, or wind turbines (WTs) are able to adjust their active and reactive power feed-in fast and almost independently from each other [2]. The usage of small DERs in grid regulation is supported by the ongoing digitalization trend and the expanding information and communication technology (ICT) infrastructure within the power system.

Besides the trend towards renewable decentralized generation and ICT, there is also a trend towards liberalization and market-based procedures in the power systems to achieve higher efficiency and lower overall costs. Currently, ancillary service provision transitions towards market-based mechanisms, which is also demanded by the EU [3]. Regarding reactive power for voltage control, at the moment, DERs are typically obliged to provide reactive power for voltage control, e.g. depending on their active power feed-in or their local voltage level. However, when reactive power provision is mandatory and without payment, grid operators are not incentivized for efficient usage [4]. Further, converters of generation units often need to be oversized to prevent curtailment of active power feed-in, which is economically inefficient again. For these reasons, reactive power markets and pricing have been important research topics with a large body of literature in the last two decades.

This work provides a comprehensive overview of various approaches how to design and analyze reactive power markets. In another recent and noteworthy survey paper about reactive power markets, Jay and Swarup [5] give a broad overview of reactive power markets and related literature, e.g. voltage control areas. While they have a strong technical focus, this work aims to focus more on the market aspects.

The associate editor coordinating the review of this manuscript and approving it for publication was S. Srivastava.

Although providing a broad overview, there are clear boundaries to the scope of this work: We do not consider active power markets or coupled active/reactive power markets. The latter are already discussed thoroughly by Jay and Swarup [5]. We also neglect *reactive power planning* – i.e. where to build reactive power sources –, even if economic aspects are considered. Furthermore, we do not consider *reactive power pricing* where the grid operator alone sets prices to compensate for reactive power without any kind of market structure or bidding. Instead, we focus on publications that presume reactive power sources that offer reactive power as a service at some kind of *reactive power market*. Our contributions are:

- In Section II, we give a short introduction to the characteristics, difficulties, and fundamentals of reactive power markets as a basis for our review. We also provide a clear distinction of *reactive power planning*, *reactive power pricing* and *reactive power markets*.
- Afterwards, we provide a comprehensive overview of the most relevant literature of the last two decades regarding design (Section III) and analysis (Section IV) of reactive power markets.
- In Section V, we give a short overview of reactive power markets already operated in the field.
- Based on the literature review, we then identify trends, research gaps, and provide some recommendations for future research (Section VI).
- Finally, we draw some general conclusions about reactive power market research in Section VII.

II. REACTIVE POWER MARKETS

Reactive power markets differ significantly from normal markets and even energy markets, which is why special market designs are required. To lay the basis for the literature review, we discuss these special characteristics first and classify reactive power markets. Finally, we introduce the relevant fundamentals of reactive power markets and how costs for reactive power are composed.

A. CHARACTERISTICS OF REACTIVE POWER MARKETS

In contrast to active power, reactive power cannot be transported over long distances, which leads to a strong local character. That results in different worth of reactive power depending on the location where its fed into the grid [6]. Similar to active power, reactive power flows must be balanced at all times. However, due to the local character, that constraint is more difficult to adhere. Another important property is that the local grid operator is the only potential buyer of reactive power as an ancillary service. That makes reactive power markets monopsonistic in nature [6]. A further consequence of the locality is that for some reactive power demand in the system only few providers can be considered, which may result in market power for these providers. That is often reinforced by current regulation which only considers generators as providers, while for example controllable loads are mostly neglected [7]. Also, in contrast to active power, reactive power is extremely cheap to produce, because no fuel is required [7]. That can result in market prices close to zero [1]. Nevertheless, in most cases, reactive power set-points cannot be set freely, because reactive capabilities are closely linked to active power feed-in of the units [7]. That interplay can be described by (P-Q)-curves and makes the analysis of reactive power markets especially difficult, because active power curtailment may be required to provide reactive power. That results in opportunity costs and affects the power flows in the system. Altogether, it is impossible for the grid operator to simply accept the cheapest offers, because the grid model and current grid state need to be considered [8]. Additionally, the small number of suppliers and the tight coupling with the physical energy system may result in drastic fluctuations and spikes of reactive power prices [4]. All these characteristics – locality, monopsonism, few providers, low production costs, interconnections with active power, and fluctuating prices – make the market design for reactive power especially difficult.

B. REACTIVE POWER PLANNING, PRICING, AND MARKETS

In the following, we give a short overview about *reactive power planning*, *reactive power pricing* and *reactive power market*, where Table 1 lists the most important differences.

TABLE 1. Distinction of reactive power planning, pricing, and markets.

	Planning	Pricing	Market
Main Actuators	Capacitors	Reactive loads	Generators
Price setting	Given by investment	By grid operator / Costs	By market rules
Communication	Not relevant	Afterwards	Beforehand
Frequency	Once	Short- or long-term	Short- or long-term
Interaction	Grid operator	Grid → Unit	Grid ↔ Unit

Reactive power planning focuses on the question where and which actuators should be built. In that field, it is often assumed that the grid operator builds the devices, mainly capacitors. Therefore, on the economic side, the investment costs are analyzed in details.

Reactive power pricing aims to find a fair distribution of the reactive power costs. Therefore, these pricing schemes can be called cost-based. They try to incentivize the owner of units like reactive loads. Sometimes, a specific control scheme for the units is assumed. The detailed price setting and billing is performed after the operation with total knowledge of the reactive power flow. The grid operator is responsible for the price setting in a one-directional way. The units have no influence on the price outcome, i.e. there is no bidding process.

Reactive power markets are used to decide on the reactive power provision by supply and demand. These markets follow specific market rules, which differ between the market designs in literature. They all include some kind of bidding process. The resulting price can be called bid-based. The market operator communicates with the actuators before the activation to agree on a price and an amount for reactive power provision in a bi-directional way, for example by an auction. Therefore, the units can actively influence the price outcome with their bidding strategy. A market scheme can work on long-term, e.g. weeks up to a year before the provision of reactive power. This kind of market is often called *procurement* in literature [9], [10]. The market can also work on short-term, where the problem is a power dispatch one. The market clearing can happen between day-ahead and close to real-time [9].

In this literature review, we focus on market-based approaches. However, sometimes a clear distinction especially between pricing and markets is difficult.

C. COSTS AND PRICING OF REACTIVE POWER

The market price for reactive power is mainly influenced by three factors. First, the costs of reactive power provision of the providing unit are important for their bidding. Second, it is relevant which type of service is paid. Finally, the market clearing method determines the actual price setting for all participants. In the following, we provide a short list for all these categories respectively.

1) COST COMPONENTS FOR REACTIVE POWER

Zhong and Bhattarcharya [11] and Lamont and Fu [12] list different costs components for reactive power:

- **Cost of loss:** The reactive power flow increases the active power loss, e.g. in field windings of a generator or in the power electronics of an inverter.
- **Switching costs:** Some reactive compensators like capacitor banks and transformers have mechanical switches that need to be exchanged after a certain number of switch operations due to wear and tear. This results in costs per switch operation.
- **Lost opportunity costs:** In synchronous generators as well as in power inverters, the maximum reactive power range is influenced by the active power output due to maximum apparent power and other aspects. As a consequence, the active power output needs to be decreased for supplying or absorbing more reactive power, if the respective limit is reached. As a consequence, the income from selling active power is reduced, leading to *lost opportunity costs*.

Note that we do not consider investment costs, because they are not relevant for bidding anymore when the unit is already installed.

2) SERVICE TYPES OF REACTIVE POWER

There are different service types that can be included in the reactive power price. Rebours *et al.* [13] name the following:

- **Fixed price:** A reactive power provider can be paid a fixed and time-independent price.
- **Availability price:** A fixed amount is only paid for the times the power plant is available for reactive power provision. This is also called capacity price.
- **Utilization payment:** A provider can be paid for its utilization, i.e. for a certain amount of reactive power feed-in.
- **Utilization frequency price:** The provider is paid depending on the amount of times the service is used.
- **Compensation of lost opportunity cost:** The reactive power provider is paid based on its lost opportunity costs.

A common rule of thumb is that the resulting reactive power price is below 1% of the active power price in a well-designed market [14], [15].

3) PRICE SETTLEMENT

The resulting market price for reactive power can be based on different settlement schemes. In general, it can be differentiated between a regulated price, which is set by a regulatory authority, and an auction-based price. For an auction, multiple ways to determine the price are possible:

- **Uniform price:** All bids are settled at the same price, which is set by the highest accepted bid. This is also called marginal price [11], [16].
- **Area-wise uniform (AWU) price:** The grid is divided into voltage control areas and an uniform price is determined in each area. Sometimes, zonal price is used as a term instead [17].
- **Nodal price:** For each node in the electrical grid, a price is selected that applies to every unit at that bus [18].
- **Pay-as-bid (PAB):** The provider is paid its offer price [16], [19].

Additionally, hybrid price settlements have been described, i.e. combinations of the described prices [16].

III. LITERATURE: MARKET-DESIGN

In the following, we give a comprehensive overview of reactive power market design literature. In most publications, the market clearing is done by an optimal power flow (OPF), which is the focus of the next Section III-A. Afterwards, we discuss non-OPF-based designs in Section III-B. In Section III-C, we focus on approaches that consider reactive power markets where grid operators exchange reactive power with each other in a market-based way.

A. OPF-BASED MARKETS

In this section, we provide a comprehensive overview of OPF-based publications and discuss their respective contributions to the state of the art, see also Table 2.

The OPF is the general method to determine the optimal steady-state operation of power grids under consideration of system constraints and control limits [20]. It was first used for reactive power procurement in the early 1990s [21]. However, the early approaches mostly assume integrated energy companies that control not only the grid but also the power plants and, therefore, all reactive power sources, which is out of scope for this work.

The first relevant publication that fits our market focus was published by Dandachi *et al.* [22] in 1996. Their general scheme is used in most publications that rely on the OPF for market clearing. Therefore, we present it in more detail here: The operators of potential reactive power sources (here: synchronous generators (SGs)) provide the transmission system operator (TSO) with a piece-wise quadratic or linear reactive power cost function that reflects the costs for reactive power provision. The TSO collects all cost functions, feeds them into an OPF solver, and determines reactive power set-points that minimize some cost function under a set of constraints. Dandachi *et al.* use a security-constrained OPF (SC-OPF) to minimize the reactive power pay-as-bid (PAB) utilization costs and the number of switching operations alternatingly.

Gil *et al.* [23] present two parallel reactive power markets: a reactive energy market for loss minimization and an additional capacity (availability) market for voltage security aspects to prevent undesirable fluctuations of the reactive power spot price. Ahmed and Strbac [24] compare capacity (availability) markets vs. utilization markets and identify not one concept as superior but that the grid operator would prefer utilization markets while unit operators prefer availability markets.

In the early 2000s, the publications of Bhattacharya and Zhong [6], [25] introduce the so called expected payment function (EPF). The EPF represents a paradigm shift to more market-focused approaches, because previous publications considered the cost function as a given fixed function. However, in a free market, the potential reactive power provider is an autonomous actor that specifies its expected payment – e.g. its bidding – freely. However, the proposed structure of the EPF is still based on the actual reactive power costs and therefore roughly quadratic (compare Figure 1). The EPF considers a combination of availability and utilization payment, allows for an obligatory amount of reactive power that does not get paid, and also enables profits for the providers. This introduces the possibility of tactical bidding or gaming to exploit market power and maximize profits. The authors investigate gaming by testing how far the providers can increase the price without losing acceptance of a bid. The authors are also the first to use uniform pricing for market clearing.

In a later publication, Zhong *et al.* [17] add voltage control areas to their approach. Voltage control areas are subareas of a power system that are only loosely coupled with the rest of the system. These consider locality better by enabling localized markets with decoupled uniform prices for each area, i.e. area-wise uniform pricing. That constitutes a middle way between pay-as-bid and uniform pricing. Later, Zhong [26] adds network devices like capacitor banks or static VAr compensators (SVCs) to the approach, which was restricted to SGs beforehand. Parida *et al.* [27] expand on the area-wise uniform approach of Zhong *et al.* by considering voltage security aspects, which was previously demonstrated by Chung *et al.* [28]. They also explicitly consider consumers of reactive power, which are often neglected in other publications.

As of 2006, El-Samahy *et al.* [29] focus strongly on the decoupling of active/reactive power markets and present a generic reactive power market framework that is compatible with arbitrary (active) energy market concepts and therefore widely deployable. The framework consists of a 2-stage approach: 1) long-term procurement of reactive power provision contracts and the respective EPFs and 2) short-term dispatch of actual reactive power usage in the form of auctions, but with fixed prices that were determined in the procurement stage. They expect the long-term procurement to solve the main issues of reactive power markets like market power or price volatility, which we discussed in Section II. In [30], they also present a reactive power model in the dispatch-stage that is the first to consider active power re-dispatch if the reactive power market resulted in active power curtailment. In [9], the same authors show the long-term procurement in detail by solving an OPF to find the optimal set of contracting generators.

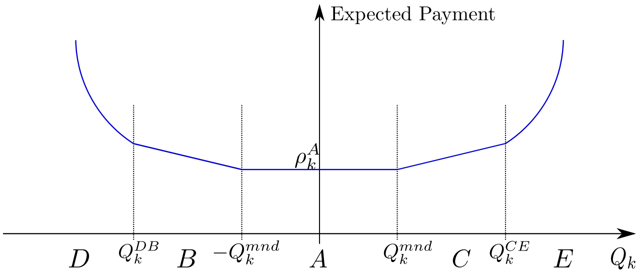


FIGURE 1. **General example for an EPF after [6], [25].**

Plavsic and Kuzle [31] propose a zonal reactive power market (area-wise uniform) with yearly tendering of capacity (availability) price and a preliminary reactive price curve. The actual price curve is then offered day-ahead, when the active power schedule is known, and must be close to the preliminary curve to prevent gaming. Cañizares *et al.* [32] combine these approaches and apply the concept to a case study of the Ontario system and energy market in southeastern Canada. Frias *et al.* [33] present a yearly capacity (availability) market. They differentiate between reactive power absorption and generation as different products and consider contingencies as well as unit unavailability.

While the previous publications assume a long-term procurement of reactive power or did not discuss the time aspect at all, Rabiee *et al.* [36], [37] discuss weaknesses of that approach, for example that long-term contracts are bad for competition. They propose a day-ahead market and also add multi-objective optimization to the state of the art. Reddy *et al.* [40] introduce voltage dependent loads as actuators and use EAs to solve the OPF. These are especially useful for multi-objective optimization as discussed by Saini and Saraswat [45] and further advanced by Roselyn *et al.* [53].

Before 2010, mainly uniform pricing was used to clear the market, because it is expected to incite providers to bid their true costs [6]. Amjady *et al.* [19] discuss that pay-as-bid pricing is superior in reactive power markets, because it reflects the locality of reactive power better and minimizes the negative impact of gaming to a single bus in the system. In [38], the same authors propose a stochastic framework that allows to consider outages of generation units to achieve more close-to-reality market results. Ahmadi and Foroud [46] also discuss nodal pricing for reactive power markets and found that classic nodal pricing is not applicable, because it

TABLE 2. Classification of discussed OPF-based reactive power markets. Devices: capacitor (cap), distributed energy resource (DER), electric vehicle (EV), micro-grid (MG), synchronous condenser (SC), superconducting magnetic energy storage (SMES), synchronous generator (SG), wind turbine (WT) Market clearing: area-wise uniform (AWU), pay-as-bid (PAB) OPF Method: differential evolutionary algorithm (DEA), evolutionary algorithm (EA), genetic algorithm (GA), particle swarm optimization (PSO) OPF Objective: maximization (max), minimization (min), multi (Multiobjective optimization with the following objectives), active/reactive power (P/Q).

	Ref.	Grid Level	Devices	Provided Service	Market Clearing	Time Intervals	OPF Method	OPF Objective
1996 – 2000	[22]	Transmission	SGs	Utilization	PAB	Clearing: 30 min	Sequential linear programming	Min costs; min number of switching operations
	[23]	Transmission	SG, SVC	Market 1: Utilization; market 2: availability	PAB	Bidding: Long-term; Clearing: 60 min	?	Min loss costs
	[24]	Transmission	SG	Utilization/ availability (in comparison)	PAB	?	Linear programming	Min costs for Q
2001 – 2006	[25]	Transmission	SG	Availability + utilization	PAB	?	GAMS: DICOPT	Min costs for loss + Q
	[6]	Transmission	SG, SC	Availability + utilization	Uniform	?	GAMS: DICOPT	Multi: min loss; min Q costs; min P change
	[17], [26]	Transmission	SG, cap, SVC	Availability + utilization	AWU	?	?	Min Q costs
	[28]	Transmission	SG, cap	Utilization	PAB	?	Sequential quadratic programming	Min costs for loss + Q
	[27]	Transmission	SG	Availability + utilization	AWU	?	GAMS: MINLP	Min Q payment to gens + payment from consumers
2007 – 2010	[30]	Transmission	SG	Availability + utilization	PAB	Bidding: Long-term; Clearing: 30-60 min	GAMS: MINOS	Min costs for Q and rebalancing P
	[34]	Transmission	SG	Availability	AWU	Long-term	GAMS: MINOS	Max societal advantage
	[35]	Transmission	SG	Availability + utilization	AWU	Bidding: Day-ahead; Clearing: 60 min	Interior point primal-dual algorithm	Min costs for loss + Q
	[33]	Transmission	SG, cap, shunt, SVC	Availability	PAB	Yearly	GAMS: DICOPT	Min costs for Q + balance services + loss + poor voltage quality
	[32]	Transmission	SG	Availability + utilization	AWU	Bidding: Long-term; Clearing: 30-60 min	GAMS: MINOS	Min costs for Q + balance services + loss
	[36]	Transmission	SG	Availability + utilization	Uniform	Day-ahead	ϵ-constraint method	Multi: min costs for Q; max voltage security margin; min overload index; min voltage deviation index
	[37]	Transmission	SG, SC	Availability + utilization	Uniform	Day-ahead	Binary GA	Min costs for Q
	[19], [38]	Transmission	SG, SC	Availability + utilization	PAB	Bidding: Day-ahead; Clearing: 60 min	GAMS: DICOPT	Min costs for Q
2011 – 2015	[39]	Distribution	SG, SC, cap	Utilization	PAB	?	Sequential quadratic programming	Multi: min costs for Q + loss; max voltage security margin
	[40]	Transmission	SG, tap-changer, shunt	Availability + utilization	Uniform	?	Strength pareto EA (+ PSO)	Multi: min costs for Q; min P loss; min L-index (voltage stability); max load served
	[41]	Distribution	MG, DER	Availability	Uniform	Day-ahead	Matpower OPF	Min costs for Q
	[42], [43]	Microgrid	SG, EV	Availability + utilization	Uniform	Bidding: Day-ahead; Clearing: 60 min	DICOPT	Min costs
	[44]	Microgrid	SG, EV	Availability + utilization	Uniform	Bidding: Day-ahead; Clearing: 60 min	PSO	Multi: Min costs; min losses
	[45]	Transmission	SG, SC	Availability + utilization	AWU	Day-ahead	Hybrid fuzzy EA	Multi: min costs for Q; min losses
	[46]	?	SG	Availability + utilization	Nodal + Availability payment	?	GAMS: SBB	Min costs for Q
	[47]	Distribution	WT	Utilization	Uniform	Day-ahead in 60 min intervals	Strength pareto EA	Multi: min costs for Q; min P curtailment; min loss; min voltage profile index
	[48]	Distribution	SG, WT	Availability + utilization	PAB	Day-ahead in 60 min intervals	GAMS: BONMIN	Min costs for Q + losses + balancing power + CO_2

TABLE 2. ***(Continued.)*** **Classification of discussed OPF-based reactive power markets. Devices: capacitor (cap), distributed energy resource (DER), electric vehicle (EV), micro-grid (MG), synchronous condenser (SC), superconducting magnetic energy storage (SMES), synchronous generator (SG), wind turbine (WT) Market clearing: area-wise uniform (AWU), pay-as-bid (PAB) OPF Method: differential evolutionary algorithm (DEA), evolutionary algorithm (EA), genetic algorithm (GA), particle swarm optimization (PSO) OPF Objective: maximization (max), minimization (min), multi (Multiobjective optimization with the following objectives), active/reactive power (P/Q).**

2016 – 2021	[49]	Transmission	?	Left open	PAB	Left open	DEA	Min costs for Q
	[50]	Transmission	SMES, cap	Utilization	Uniform	12 h	DEA with random localization	Min P loss
	[51]	Transmission	SG	Availability + utilization	PAB	Long-term	?	Multi: min costs for Q; max voltage stability margin
	[52]	Transmission	SG	Availability + utilization	Uniform	?	GAMS: DICOPT	Min costs for Q
	[53]	Transmission	SG, cap	Availability + utilization	PAB	Bidding: Long-term; Clearing: Day-ahead?	Hybrid PSO	Multi: min costs for Q; min costs of loss; min voltage stability index
	[54]	Transmission	SG	Availability + utilization	Separated pricing	?	GA	Min costs for Q; max players profit
	[55]	Transmission	SG	Utilization	AWU	Day-ahead in 60 min intervals	GAMS: DICOPT	Min costs
	[56]	Transmission	SG, SC	Availability + utilization	Uniform	Day-ahead in 60 min intervals	GAMS: ?	Min costs for Q

insufficiently considers non-variable costs, which are especially relevant for reactive power. They propose a modified nodal pricing method that adds additional availability payment and also considers contingencies.

From 2011 on, the research focus shifts from transmission grids to distribution systems. Kargarian and Raoofat [39] as well as Rueda-Medina and Padilha-Feltrin [47] add stochasticity of wind turbines to the state of the art. Madureira and Lopes [41] also consider micro-grids (MGs) as reactive power providers and discuss aggregation of DERs. Samimi *et al.* [48] focus on DERs as well, but also discuss interdependencies with the active power market. They further consider other grid operators as reactive power market participants and add CO_2 costs to the objective function. Farahani *et al.* [42] discuss how EV charging stations can participate in OPF-based reactive power markets. Later, they expand their framework by multi-objective optimization [44] and contingencies [43]. Mojdehi *et al.* [57] discuss optimal participation of EVs in reactive power markets from the EV operator's perspective.

Khandani and Foroud [51] propose a joint reactive power and reactive reserve market. Toulabi and Samimi [56] advance this research direction by considering reliability and outages or reactive power providers in the optimization by using a Monte-Carlo simulation.

From 2017 on, multiple publications propose combinations of reactive power markets and reactive power pricing (see Section II-B for distinction): Sahraie *et al.* [54] question if conventional pricing methods like uniform or PAB pricing are actually the best choice for reactive power markets. They propose a custom pricing scheme that incorporates the market participants' profits in the optimization, which results in higher incentives compared to PAB and higher efficiency compared to uniform pricing. In [58], the same authors propose a multi-objective optimization with arbitrary objective functions, which enables grid operators to choose their own preferences for their local reactive power market. Jay and Swarup [55] propose a market clearing where providers are not only paid by their EPF but also by their value for grid operation. Ahmadimanesh and Kalantar [52] consider reactive power losses caused by active power feed-in of the market participants in the market clearing, which increases fairness of the market result.

The following publications are OPF-related but are quite extraordinary by proposing unusual ways for reactive power markets that are very different from the standard approach presented at the beginning of the section. Lin *et al.* [49] propose an interesting concept of a voltage control market in disturbance situations where no reactive power is traded, but the voltage deviation effect of it, which considers the locality of reactive power inherently. Most of the previous publications assume the grid operator to be market operator and also the only purchaser of reactive power in a single auction. In contrast, Biswas *et al.* [50] propose a double auction approach where the grid operator is only market operator but not market participant. Instead, units serve as customers and/or providers, which makes the market non-monopsonistic. Tamimi *et al.* [59] compare different OPF formulations and especially the modelling of the reactive power limits. They point out a trade-off between precision and market efficiency on the one hand and computing time on the other hand. Also relevant in the context of OPF-based reactive power markets, Beagam *et al.* [60] propose a pure DC Q flow model that is faster than a normal OPF. The concept is similar to the DC-OPF that is often used for active power market clearing.

In Table 2, the discussed OPF-based publications are listed chronologically. The publications are classified by their grid-level, considered reactive power providing devices, if reactive power utilization or availability is remunerated, how the market is cleared, when bidding and market clearing happen, and finally the objective function of the OPF and what method was used to solve it. Often, the information is not explicitly given. Especially the grid-level was often guessed from context or derived from the benchmark system that was used. The market clearing method could be derived from the payment function to minimize. The times and intervals for bidding and dispatch are often not discussed, indicated by the question marks.

The table shows that most publications focus on transmission grids and SGs or SCs as reactive power providers. Only occasionally, distributions grids and other devices like WTs or EVs are considered. The paid service is mostly both the combination of utilized reactive power and available capacity, which probably results from the fact that most publications adopt the EPF of Zhong and Bhattacharya [6], which considers both in combination. In contrast, there is complete disagreement regarding PAB, uniform pricing, or area-wise uniform pricing. Other approaches like nodal pricing are barely considered. Lots of publications propose a day-ahead reactive power market that is cleared in hourly intervals. However, it seems that most publications do not consider such temporal aspects as relevant, since they are not discussed in detail. Regarding the OPF, there is a trend visible from conventional optimization methods to meta-heuristics and also to multi-objective optimization.

B. NON-OPF-BASED MARKETS

Only few publications propose a market system without using an OPF to clear it.

Von Appen *et al.* [61] analyze the minimal costs for reactive power in a micro-grid and for providing reactive power to the upper grid. They use a central solver to compare four different approaches to purchase reactive power: Capacity (Availability) compensation, utilization compensation, percentage reduction of distribution charge and an incentive approach that penalizes certain power factors. They conclude that the micro-grid is a good provider of reactive power to the upper grid and that an availability compensation as well as an utilization compensation send the right price signal.

Kumano and Kimiduka [62] describe an approach to price reactive power for voltage regulation. Each PV system is responsible to hold its grid voltage in the restricted limits. As first step, it can vary its own reactive power supply or demand. If this is not enough, it can either buy reactive power support from the devices nearby or it is required to reduce its own active power injection. Each PV system can offer reactive power to the other ones. The monetary transactions are only done between the PV systems and the price for reactive power is fixed. They propose to calculate the price based on possible grid side costs. The distribution system operator (DSO) does not participate in this concept and only profits from the system.

Koide *et al.* [63] proposed a real-time pricing scheme for reactive power. The price is paid for utilization and is decided close to real-time by the DSO. At a given price, each owner of a distributed generator can decide if the generator should deliver reactive power for that price. If the offered amount of reactive power is not enough, the DSO can re-adjust the price.

Another interesting non-OPF-based market mechanism was presented by Jay and Swarup [64]. First, the reactive power providers submit their bids to the grid operator, which then solves an optimization problem for the optimal non-uniform price signal. In contrast to OPF-based approaches, the price is then communicated to the generators, which set their reactive set-points by themselves, based on that price signal, leaving them more autonomy. Using a game theoretical approach, the authors show that the approach induces truth-telling behavior of the market participants and non-negative profits. The market clearing is done in an area-wise way, similar to [17]. However, Jay and Swarup discuss that voltage-control areas considering only reactive power are not sufficient due to potential coupling of active power and voltage. They propose voltage-apparent power areas instead.

C. GRID-LEVEL MARKETS

Most previously discussed publications propose local reactive power markets where a single grid operator optimizes reactive power procurement for its own system. However, in future power systems, most potential for reactive power will be provided by DERs in distribution systems while TSOs will have difficulties to procure reactive power due to decreasing number of large conventional power plants. Hinz and Most [65] investigated the reactive power potential of distribution systems for the transmission grid and found large economical and technical advantages. This potential would remain unused in fragmented local markets, where the coordination of grid operators is not explicitly considered [66]. However, due to the locality of reactive power, a simple aggregation or a central marketplace is not possible, because reactive power procurement from DERs in neighbored systems must not result in local congestions there [67]. Therefore, coordination between the providing DERs, the local grid operator and the procuring grid operator should be considered, which requires multi-grid reactive power market frameworks. That coordination is especially difficult if each grid operator implements its own local market, which all may be incompatible with each other. Besides the additional service potential for the TSO, multi-grid markets would increase the number of market participants drastically, which could partly solve the problem of market power. Not only would that allow for more providers of reactive power, but also for more than a single customer. That may dissolve the monopsonistic nature of local reactive power markets and increase social welfare. Consequently, TSO-DSO coordination is another important requirement for the design of reactive power markets and ancillary service markets in general [8]. Also, the reactive power provision of micro-grids can be relevant for reactive power markets, as discussed by von Appen *et al.* [61].

Doostizadeh and Ettehadi [68] consider distribution systems as fictitious compensators connected to the superordinate network. They propose repeated power flow calculations to determine reactive power capability and an EPF for each distribution system as a whole. This way, distribution systems can participate in the reactive power market of the superordinate system, if it follows the EPF-based mechanism described in Section III-A. The approach of Pudjianto *et al.* [69] is very similar, but uses repeated OPF calculations to determine the cost function and reactive power constraints at the intersection point. They consider the reactive power providers connected to the distribution grid as a virtual power plant. However, the exact market rules remain unclear. The same approach is used by Tang *et al.* [70]. In addition, they define the TSO-DSO interaction in detail: First, the TSO sends its reactive demand request to the DSO. Second, the DSO sends a cost function of its system to the TSO. Then, the TSO clears its local market, incorporating the DSO cost functions. Finally, the TSO communicates the resulting reactive power setpoints to the DSO, which then clears and optimizes its local market. Therefore, it is a methodology to couple multiple local reactive power markets. In their innovative publication, Retorta *et al.* [71] consider a multi voltage level framework where the TSO requests reactive power from the DSO, which is then procured in a local reactive power market similar to the standard OPF-based framework described in III-A. Apart from the multi-grid aspect, they further contribute very detailed descriptions of the market process and the communication, a close to real-time framework, a rolling window market clearing, incremental bidding relative to the current state of the system, and more complex bids than simple cost functions to consider e.g. a limited number of asset switching actions. However, a complex multi-period OPF must be solved repeatedly for a single market clearing, because the results are discarded when a condition for the complex bids does not hold. Further, payment of the TSO for the service is not considered, which makes the approach economically inefficient to some extend, because the TSO has no incentive to request reactive power from distribution grids that provide it cheaply.

All the above mentioned approaches assume a single point of coupling between the distribution system and the transmission system. None of them considers horizontal connection points, which would be relevant for the reactive power exchange between multiple transmission systems. Also, none of them considers more than two voltage levels, which implicitly assumes that the whole distribution system from low voltage to high voltage is controlled by a single DSO. Further, the above discussed publications mainly propose solutions how to couple multiple local reactive power markets with the respective grid operator as market operator. In contrast to that, Hillberg *et al.* [67] discuss the possibility of a single central market place for flexibility in general, not only reactive power. They also discuss requirements that must be fulfilled for a multi-grid market framework, which are all applicable to non-central markets as well, namely market access, liquidity, information flow, and data security and privacy.

Most of the publications propose markets that are operated by the DSO, which aggregates the services to a central TSO market. According to Gerard *et al.* [66], this is called a local ancillary service market. They discuss four alternative solutions how ancillary service markets at the TSO-DSO interface can be operated. However, these are not considered at all in the reactive power market literature yet.

IV. LITERATURE: MARKET POWER AND MARKET MANIPULATION

While the previous section discussed different designs, the following section focuses on the analysis of reactive power markets considering market power, market manipulation, and game theory for bidding strategies.

The aspect of market power was mentioned several times already. Market power can be defined as the ability to hold the price above the competitive level, exclude competitors from the market, or to control the total output of the market [72]. There is consensus that due to the physical system constraints and entry barriers, exercise of market power in energy markets is especially relevant and also difficult to detect [73]. Due to the locality of reactive power and, therefore, the reduced competition, market power is an even bigger problem in reactive power markets [74]. Chicco [75] even states that the exercise of market power cannot be completely avoided. Possible negative consequences of market power are withholding of generation by participants, wealth transfer from consumers to producers, decrease of market efficiency, and welfare loss [7]. In the following, we discuss market power in reactive power markets. For a more general review of market power in energy markets, refer to [72] and [73].

Lots of indices to measure market power are discussed in literature. However, due to the local and monopsonistic nature of reactive power markets, standard market power indices like the Herfindahl-Hirschman Index (HHI) [76] are not directly applicable without adjustment (refer to [72] for a comprehensive list of relevant indices in energy markets).

Alvarado and Overbye [74] discuss the application of the HHI to measure the market power potential in reactive power markets. They note that locality and grid condition should be considered for market power indices and adapt the original HHI to consider these two by calculating the voltage sensitivity with respect to reactive power provision of each generator. This way, the degree of market concentration at specific locations of the system can be calculated. However, they focus only on the capability of generators to manipulate system voltage. Souza *et al.* [77] expand on that approach and focus on the market power potential in relation to the system condition. In their experiments, they found rising reactive market power potential when system load increases. Using the same approach, de Mello Honório *et al.* [78] propose the countermeasure that grid operators should prevent players with a high market power to connect new units to buses that are already vulnerable to market power exercise. Chicco [75] further expands the approach again by considering PV type buses with constant voltage and the market share of the slack bus, which were neglected in previous publications.

Souza *et al.* [77] introduce the concept of must-run generators, which are so important for grid operation that they must provide reactive power in any case. Therefore, the grid operator is forced to procure reactive power from these generators, which gives them market power. Feng *et al.* [79] introduce a market power metric that is based on must-run indices. They also aggregate groups of generators that are controlled by the same generation company. Further, they point out that not only the voltage constraints should be considered in reactive market power analysis, but also line loading and voltage stability. Asgari *et al.* [7] compute another must-run index by minimizing reactive power procurement. If that minimization results in reactive power values greater than zero, that means that the grid operator is forced to procure reactive power for constraint satisfaction and that the respective generation company holds market power potential.

While the previously discussed publications introduce ways to measure market power or its potential, Oh and Thomas [80] discuss an actual gaming strategy in which market power can be used to improve profits on coupled active and reactive power markets by strategic bidding. Chitkara *et al.* [81] investigate exercise of market power by modelling and optimizing not only the market operation but also the bidding behavior of all participating generators. In their case studies, they simulate the consequences of grid operator controlled generators, synchronous condensers, and caps on uniform reactive power price outcome. Samii *et al.* [82] have a similar approach. They use a game theoretic problem formalization to model the market participants bidding strategy and use their willingness to change their bidding strategy as an indicator for market power.

Soleymani [83] models the bidding behavior of agents that participate in a reactive power market, considering a parallel energy market. The author formulates the incomplete game as bi-level optimization problem. The solution of that game is the Bayesian Nash equilibrium, which considers uncertainty about competitors' bidding strategies. Zhang *et al.* [84] formulate a non-cooperative voltage regulation game in a nodal pricing setting. They consider the grid operator, suppliers, and loads as actors and prove the existence of a Nash equilibrium. Patel *et al.* [85] discuss that it is very difficult to find optimal bidding strategies in reactive power markets, because of the difficulty to estimate strategies of other participants and because of the strong coupling with the physical system. They use Reinforcement Learning to learn optimal bidding, which overcomes these difficulties, because no explicit assumptions about other market participants or the energy system are required. Wolgast *et al.* [86] train a Reinforcement Learning agent as well to use controllable loads in a reactive power market setting. The agent learns to induce constraint violations into the system to enforce reactive power demand. This way, it manipulates the system in a way to increase generators' market power by making them must-run, which increases their profit without changing the generators' behavior. They identify the hard constraints of the OPF as weakpoint that enables this strategy.

V. REAL-WORLD EXAMPLES OF REACTIVE POWER MARKETS

While different concepts for reactive power markets are proposed in literature, some countries already apply market-like methods to procure reactive power. Often, authors summarize multiple existing real-world reactive power markets when introducing new concepts in literature, e.g. Zhong and Battacharya in 2002 [11] or Sirviö *et al.* in 2018 [87]. To our knowledge, a comprehensive review of already existing reactive power markets is still missing, but also out of scope for this work. So, we will only provide a broad overview here. The reactive power service is often structured in two parts. In the first part, a lot of countries, e.g. Australia, France, Germany, United Kingdom, New Zealand, Spain and Sweden, require specific types of power plants to provide reactive power in a certain range. As the second part, additional support is often arranged by using bilateral contracts like in the United Kingdom by using some kind of tendering process, e.g. an auction mechanism [88].

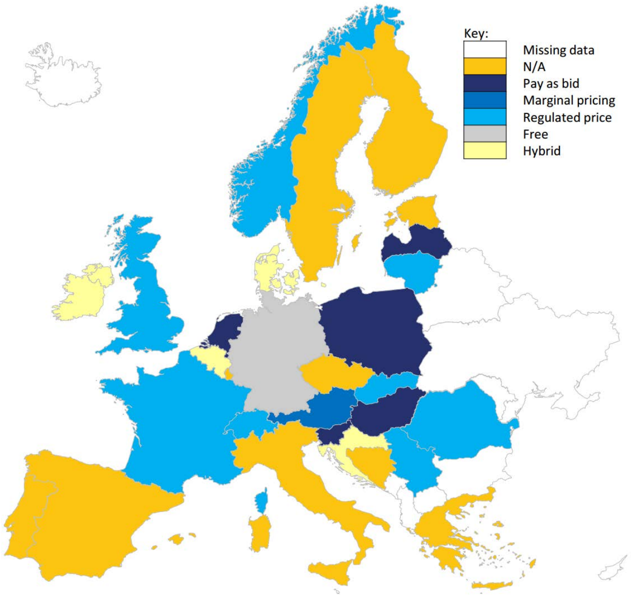


FIGURE 2. Settlement rules for voltage control in different countries [16].

Currently, reactive power procurement lacks competition in different countries, e.g. Australia, the United Kingdom, or the United States. The prices for reactive power are dominated by administratively determined pricing methodologies [89].

An overview of the procurement for voltage regulation is summarized in Fig. 2 based on a review by the European Network of Transmission System Operators for Electricity (ENTSO-E) [16]. We already introduced the different price settlement rules in Section II-C3. The figure shows a mixture of different settlement rules that vary between the countries. While some countries regulate the prices, others use PAB, uniform pricing or hybrid price systems.

One example for a hybrid price system is Belgium. The reactive power service in Belgium is structured in two parts: primary and centralized control. Within the primary control, power plants with a rated power of 25 MW and more need to automatically supply reactive power in a certain range to support voltage regulation and are paid for reactive power availability based on a regulated price [90], [91]. The centralized control is based on a tender process where the best bid, based on financial, economic and geographic terms, is selected [90]. The units get paid a fixed price for installing IT and technical adaptation as well as an utilization price for each Mvarh [92]. Both services are based on at least one year contracts.

VI. TRENDS, RESEARCH GAPS & RECOMMENDATIONS

In the following, we discuss trends in reactive power market research, identify research gaps in the literature, and derive some general recommendations for future research in the field.

A. TRENDS

From the general trends in the energy system and the literature overview in Section III to IV, we can derive some trends for reactive power market research.

1) SMALL DERs

The most important general trend is the transition towards smaller units that are connected to the distribution systems, e.g. wind turbines, PV systems, EV chargers, and so on. Also, these units often have a high controllability in the sense that they are very dynamic and that active/reactive power are not highly coupled with each other. However, their availability is highly fluctuating and often depends on external factors like wind speed, solar radiation or user behavior. With regard to reactive power markets, that requires markets and optimization algorithms that consider uncertainty, which is an important trend of the recent years, considered for example by refs. [38], [47]. The fluctuating availability also results in a trend towards shorter time-scales of ancillary service markets [93]. However, according to Table 2, that trend is not visible in reactive power market literature yet.

2) DISTRIBUTION SYSTEM

Most of the mentioned new reactive power providers are connected to the distribution system. While older reactive power market literature focuses mainly on the transmission system, since 2011 more and more publications discuss the possibility of markets on distribution level. That bears not only challenges like smaller power plants, higher uncertainty, or less available ICT infrastructure, but also allows for a large number of new market participants and enables better local reactive power provision.

3) MULTI-GRID MARKETS

While most new reactive power availability emerges on the distribution level, reactive power availability in the transmission systems decreases. Consequently, another research trend is how multiple local reactive power markets can be coupled so that transmission operators can procure reactive power from plants that are connected to the distribution system, as discussed in III-C.

4) COUPLED ACTIVE/REACTIVE MARKETS

Also highly entangled with the trend to distribution systems is the trend towards coupled active and reactive power markets, because active power cannot be neglected when distribution systems are considered. That complicates the implementation of independent reactive power markets drastically. However, these coupled markets are out of scope here. For an extensive overview, refer to [5].

5) MANIPULATION

Another trend focuses on the market participants' behavior and how reactive power markets can be manipulated. While older literature focuses mostly on metrics how to calculate market power potential, a small body of recent literature actually models and optimizes the bidding behavior of the participants that can be expected to result from the given market rules.

B. RESEARCH GAPS

The literature overview in Section III and IV demonstrates that reactive power market literature is mainly focused on OPF-based market designs and on the advancement of the OPF for market clearing. Other relevant aspects receive only little research attention, resulting in some serious research gaps.

1) AUTONOMOUS ACTORS

The most important research gap is the lack of attention to the market participants, i.e. the reactive power providers. In a free market, the market participants need to be considered as autonomous actors that aim to maximize their overall market profit. However, most mentioned market design publications do not consider profit-maximizing bidding behavior. Instead, market participants mostly bid with a fixed cost-based EPF. This way, the quality of the market design can hardly be assessed.

2) PRICING

A resulting research gap is the open question whether uniform or pay-as-bid pricing should be used in reactive power markets [37]. Both approaches are used in roughly half of the publications and in both cases the respective authors claim that their approach is superior by preventing exercise of market power, e.g. [19] for pay-as-bid and [6], [37] for uniform pricing. A systematic comparison of both approaches under consideration of the respective resulting rational bidding behavior would be necessary to explore which approach better addresses the specific challenges of reactive power markets. However, there is also the possibility that none of the standard approaches is best and that custom pricing mechanisms are required for the very special case of reactive power markets.

3) GAMING

In a similar fashion, a systematic search for the possibility of market power exercise and gaming strategies is necessary to rule out the possibility of undesired incentives. Game theory and Reinforcement Learning are possible approaches here, as shown in [83] and [86] respectively.

4) MECHANISM DESIGN

In general, most market design publications only superficially explain and justify their choice of market rules. Again, a systematic comparison of design decisions would be helpful to determine optimal market rules, under consideration of the rational bidding behavior of all market participants. This gap can be clearly seen in the lack of cited market design, mechanism design [94] and automated mechanism design [95] literature. Mechanism design is the search for game rules that achieve some objective although all participating actors are self-interested. Similarly, almost no publications from the fields of market theory or smart markets [96] are cited. Smart markets are pool-based periodic auctions that are cleared by optimization algorithms under consideration of constraints. Thus all OPF-based reactive power markets belong to this category.

5) GRID-LEVEL MARKETS

In Section III-C, we discussed the small body of literature focusing on grid-level reactive power markets. Although the interest in this research area has grown since 2019, there are still lots of unresolved questions, for example how to deal with multiple coupling points, how to communicate the highly non-linear cost function, or how to deal with horizontal coupling points between multiple grids.

6) REAL-WORLD TRANSFER

The overview of proposed market designs in Section III in comparison to the real-world overview in Section V clearly demonstrates that there is also a large gap between research and the real-world. While the literature since the 1990s focuses on OPF-based market designs, such reactive power markets seem to be not used in practice yet. However, the reason for this gap is not obvious. One question that most reactive power market publications neglect are the actual requirements necessary for the implementation of a reactive power market, e.g. regarding communication, accounting, regulation, etc. Another notable point here is certainly the lack of ICT infrastructure and automation – especially in the distribution system – that would be required so that not only large power plants can participate in reactive power markets.

7) MARKET OPERATOR

Besides these clear research gaps, we see some implicit assumptions in the literature that are barely challenged. Most market design publications seem to assume that the grid operator defines the market rules and acts as market operator. This assumption gives a lot of power to the grid operator, who has monopsonistic market power anyway. Advantages of this assumption are that the grid operator can define optimal market rules and objective functions for grid stability. However, it can be expected that the grid operator will be favored by the resulting market rules, compared to the other participants. That could be negative regarding overall welfare and reduce incentives for reactive power providers to invest. On the other hand, it may very well be impossible for a third-party market operator or regulator to find optimal market rules, because of the tight coupling between reactive power markets and the physical energy system. While most publications assume that market rules can be applied to all kinds of power systems, Wolgast *et al.* [86] suspect that market rules for local markets have to be designed in a grid-specific way to consider its respective characteristics and regulations. If that is the case, a grid model would be required for market design, which again favors the grid operator to define the market rules.

C. RECOMMENDATIONS

We mentioned already that the reactive power market literature is quite one-dimensional. While the formulation and solution of the OPF problem is often presented thoroughly, other aspects are not discussed in detail. Because of this and in addition to the previously listed research gaps, we would like to point-out some loose recommendations what to consider in more detail for future publications in the reactive power market domain:

1) OPEN MARKETS

Most market designs consider only a small subset of reactive power providers, often only synchronous generators (compare Table 2). To reduce market power and to achieve optimal reactive power procurement, future market designs should aim for possible participation of arbitrary unit types that can provide reactive power [6], [29], [36].

2) MODULARITY

The discussed publications all present market rules and OPF objective function as a unit. However, grid operators that implement a local reactive power market want to choose their own objective function based on their own specific demands. Consequently, reactive power market designs should be modular to allow for exchangeable and grid-specific objective functions [58].

3) TIME-SERIED DATA

Most publications test their market design on a single grid state. However, ancillary service markets must yield good outcomes over the whole year. Therefore, it would be helpful to test a new market design on realistic long-term time-series data, if such data is available.

4) REGULATORY FRAMEWORK

As discussed before, by including information about the assumptions regarding regulation, the comparability of the approaches can be increased. Who is the market operator? Which agents have which responsibilities and obligations?

5) TIME

Similarly, most publications do not discuss time aspects in detail (see Table 2). When a new market design is proposed, it would be helpful to discuss when bids are submitted, when the market clearing is performed, how long bids and market results are valid, etc. A detailed example how this can be done is ref. [71].

6) DATA FLOW

Most discussed publications do not explicitly state which actors communicate which information with the grid operator. Since we consider multiple self-interested actors, it should be explicitly discussed which information the participants are required to share. Further, it should be discussed whether the agents can be expected to share that information truthfully. Finally, it could be stated which information the market operator shares with the participants. For example, none of the publications stated if the full market outcome – i.e. all resulting prices – is communicated to each participant after clearing. That information can be expected to highly influence their future behavior. This requires standardization of the information interfaces between the actors.

We are aware that each publication has its own focus and that it is not sensible to always consider all these points. However, we believe that future reactive power market research would benefit significantly by consideration of these recommendations.

VII. CONCLUSION

The current transformation of the energy system brings a new demand for reactive power market research to procure reactive power efficiently. With the goal to present the current state of the art, we gave a general overview of reactive power markets, their characteristics and relevant fundamentals. That laid the basis for a comprehensive literature overview. Most publications present reactive power market designs that are cleared by solving an OPF. However, we also discussed non-OPF-based markets, markets on grid-level, and methodologies how to analyze reactive power markets regarding market power, bidding behavior, and market manipulation. After giving a short overview of real-world examples, we discussed trends, research gaps, and gave some recommendations what to consider in future reactive power market research. Overall, it can be concluded that past research is one-dimensionally focused on OPF-based market design while other important topics are strongly neglected. Further, the literature overview showed a strong focus on how to solve optimization problems while market aspects and the perspectives of market participants are not considered sufficiently.

REFERENCES

[1] A. G. Isemonger, "Some guidelines for designing markets in reactive power," *Electr. J.*, vol. 20, no. 6, pp. 35–45, Jul. 2007.

[2] M. Braun, "Technological control capabilities of DER to provide future ancillary services," *Int. J. Distrib. Energy Resour.*, vol. 3, no. 3, pp. 191–206, 2007.

[3] European Union. (Jun. 5, 2019). *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU*. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0944

[4] K. Banerjee, P. Mitra, A. Sarkar, Y. Liu, and S. Chathadi, "Reactive power markets: A possible future?" in *Proc. 45th North Amer. Power Symp. (NAPS)*, Sep. 2013, pp. 1–6.

[5] D. Jay and K. S. Swarup, "A comprehensive survey on reactive power ancillary service markets," *Renew. Sustain. Energy Rev.*, vol. 144, Jul. 2021, Art. no. 110967.

[6] J. Zhong and K. Bhattacharya, "Toward a competitive market for reactive power," *IEEE Trans. Power Syst.*, vol. 17, no. 4, pp. 1206–1215, Nov. 2002.

[7] M. H. Asgari, H. Monsef, and M. O. Buygi, "A novel approach for evaluating market power in reactive power markets," *Eur. Trans. Electr. Power*, vol. 21, no. 5, pp. 1731–1745, Jul. 2011.

[8] E. Heilmann, N. Klempp, and H. Wetzel, "Market design of regional flexibility markets: A classification metric for flexibility products and its application to German prototypical flexibility markets: MAGKS joint discussion paper series in economics," School Bus. Econ., Philipps-Univ. Marburg, Marburg, Germany, Tech. Rep. 02-2020, 2020. [Online]. Available: http://hdl.handle.net/10419/213475

[9] I. El-Samahy, K. Bhattacharya, C. Canizares, M. F. Anjos, and J. Pan, "A procurement market model for reactive power services considering system security," *IEEE Trans. Power Syst.*, vol. 23, no. 1, pp. 137–149, Feb. 2008.

[10] A. Singh, P. K. Kalra, and D. S. Chauhan, "New approach of procurement market model for reactive power in deregulated electricity market," in *Proc. Int. Conf. Power Syst.* Piscataway, NJ, USA: IEEE, 2009, pp. 1–6.

[11] J. Zhong and K. Bhattacharya, "Reactive power management in deregulated electricity markets—A review," in *Proc. Power Eng. Soc. Winter Meeting*. Piscataway, NJ, USA: IEEE, 2002, pp. 1287–1292.

[12] J. W. Lamont and J. Fu, "Cost analysis of reactive power support," *IEEE Trans. Power Syst.*, vol. 14, no. 3, pp. 890–898, Aug. 1999.

[13] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, "A survey of frequency and voltage control ancillary services—Part I: Technical features," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 350–357, Feb. 2007.

[14] S. Hao and A. Papalexopoulos, "Reactive power pricing and management," *IEEE Trans. Power Syst.*, vol. 12, no. 1, pp. 95–104, Feb. 1997.

[15] A. Rabiee, H. Shayanfar, and N. Amjady, "Reactive power pricing—Problems & a proposal for a competitive market," *IEEE Power Energy Mag.*, vol. 7, no. 1, pp. 18–32, Jan./Feb. 2009.

[16] ENTSO-E. (May 2020). *Survey on Ancillary Services Procurement, Balacing Market Design 2019*. [Online]. Available: https://eepublicdownloads.azureedge.net/clean-documents/mc-documents/200505_WG_AS_survey_ancillary_services_2019.pdf

[17] J. Zhong, E. Nobile, A. Bose, and K. Bhattacharya, "Localized reactive power markets using the concept of voltage control areas," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1555–1561, Aug. 2004.

[18] M. C. Cerbantes, J. R. S. Mantovani, R. Fernández-Blanco, and M. A. Ortega-Vazquez, "A nodal pricing approach for reactive power in distribution networks," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf., Latin Amer., ISGT Latin Amer.*, Sep. 2017, pp. 1–6.

[19] N. Amjady, A. Rabiee, and H. A. Shayanfar, "Pay-as-bid based reactive power market," *Energy Convers. Manage.*, vol. 51, no. 2, pp. 376–381, Feb. 2010.

[20] S. Frank, I. Steponavice, and S. Rebennack, "Optimal power flow: A bibliographic survey I: Formulations and deterministic methods," *Energy Syst.*, vol. 3, no. 3, pp. 221–258, Apr. 2012.

[21] M. L. Baughman and S. N. Siddiqi, "Real-time pricing of reactive power: Theory and case study results," *IEEE Trans. Power Syst.*, vol. 6, no. 1, pp. 23–29, Feb. 1991.

[22] N. H. Dandachi, M. J. Rawlins, O. Alsac, M. Prais, and B. Stott, "OPF for reactive pricing studies on the NGC system," *IEEE Trans. Power Syst.*, vol. 11, no. 1, pp. 226–232, Feb. 1996.

[23] J. B. Gil, T. G. S. Roman, J. J. A. Rios, and P. S. Martin, "Reactive power pricing: A conceptual framework for remuneration and charging procedures," *IEEE Trans. Power Syst.*, vol. 15, no. 2, pp. 483–489, May 2000.

[24] S. Ahmed and G. Strbac, "A method for simulation and analysis of reactive power market," *IEEE Trans. Power Syst.*, vol. 15, no. 3, pp. 1047–1052, Aug. 2000.

[25] K. Bhattacharya and J. Zhong, "Reactive power as an ancillary service," *IEEE Trans. Power Syst.*, vol. 16, no. 2, pp. 294–300, May 2001.

[26] J. Zhong, "A pricing mechanism for network reactive power devices in competitive market," in *Proc. IEEE Power India Conf.* Piscataway, NJ, USA: IEEE Operations Center, Apr. 2006, p. 6.

[27] S. K. Parida, S. N. Singh, and S. C. Srivastava, "Voltage security constrained localized reactive power market," in *Proc. IEEE Power India Conf.* Piscataway, NJ, USA: IEEE Operations Center, Apr. 2006, p. 6.

[28] C. Y. Chung, T. S. Chung, C. W. Yu, and X. J. Lin, "Cost-based reactive power pricing with voltage security consideration in restructured power systems," *Electr. Power Syst. Res.*, vol. 70, no. 2, pp. 85–91, Jul. 2004.

[29] I. El-Samahy, K. Bhattacharya, and C. Cañizares, "A unified framework for reactive power management in deregulated electricity markets," in *Proc. IEEE PES Power Syst. Conf. Expo.* Piscataway, NJ, USA: IEEE Service Center, Oct./Nov. 2006, pp. 901–907.

[30] I. El-Samahy, C. A. Canizares, K. Bhattacharya, and J. Pan, "An optimal reactive power dispatch model for deregulated electricity markets," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*. Piscataway, NJ, USA: IEEE Service Center, Jun. 2007, pp. 1–7.

[31] T. Plavsic and I. Kuzle, "Zonal reactive power market model based n optimal voltage scheduling," in *Proc. AFRICON*, Sep. 2007, pp. 1–7.

[32] C. A. Ca nizares, K. Bhattacharya, I. El-Samahy, H. Haghighat, J. Pan, and C. Tang, "Re-defining the reactive power dispatch problem in the context of competitive electricity markets," *IEEE Trans. Power Syst.*, vol. 4, no. 2, pp. 162–177, Feb. 2010.

[33] P. Frias, T. Gomez, and D. Soler, "A reactive power capacity market using annual auctions," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1458–1468, Aug. 2008.

[34] M. E. El-Hawary, *Introduction to Electrical Power Systems* (IEEE Press Series on Power Engineering), vol. 50. Hoboken, NJ, USA: Wiley, 2008. [Online]. Available: http://gbv.eblib.com/patron/FullRecord.aspx?p=406465

[35] T. Plavsic and I. Kuzle, "Zonal reactive power market model based n optimal voltage scheduling," in *Proc. AFRICON*, Sep. 2007, pp. 1–7.

[36] A. Rabiee, H. Shayanfar, and N. Amjady, "Multiobjective clearing of reactive power market in deregulated power systems," *Appl. Energy*, vol. 86, no. 9, pp. 1555–1564, Sep. 2009.

[37] A. Rabiee, N. Amjady, and H. Shayanfar, "Reactive power market development considering power system security," *Electr. Eng.*, vol. 92, nos. 4–5, pp. 151–164, Oct. 2010.

[38] N. Amjady, A. Rabiee, and H. A. Shayanfar, "A stochastic framework for clearing of reactive power market," *Energy*, vol. 35, no. 1, pp. 239–245, Jan. 2010.

[39] A. Kargarian and M. Raoofat, "Stochastic reactive power market with volatility of wind power considering voltage security," *Energy*, vol. 36, no. 5, pp. 2565–2571, May 2011.

[40] S. S. Reddy, A. R. Abhyankar, and P. R. Bijwe, "Reactive power price clearing using multi-objective optimization," *Energy*, vol. 36, no. 5, pp. 3579–3589, May 2011.

[41] A. G. Madureira and J. A. P. Lopes, "Ancillary services market framework for voltage control in distribution networks with microgrids," *Electr. Power Syst. Res.*, vol. 86, pp. 1–7, May 2012.

[42] H. F. Farahani, H. A. Shayanfar, and M. S. Ghazizadeh, "Incorporation of plug in hybrid electric vehicle in the reactive power market," *J. Renew. Sustain. Energy*, vol. 4, no. 5, Sep. 2012, Art. no. 053123.

[43] H. F. Farahani, H. A. Shayanfar, and M. S. Ghazizadeh, "Modeling of stochastic behavior of plug-in hybrid electric vehicle in a reactive power market," *Electr. Eng.*, vol. 96, no. 1, pp. 1–13, Mar. 2014.

[44] H. F. Farahani, H. A. Shayanfar, and M. S. Ghazizadeh, "Multi-objective clearing of reactive power market including plug-in hybrid electric vehicle," *Electr. Power Compon. Syst.*, vol. 41, no. 2, pp. 197–220, Jan. 2013.

[45] A. Saini and A. Saraswat, "Multi-objective day-ahead localized reactive power market clearing model using HFMOEA," *Int. J. Electr. Power Energy Syst.*, vol. 46, pp. 376–391, Mar. 2013.

[46] H. Ahmadi and A. A. Foroud, "A stochastic framework for reactive power procurement market, based on nodal price model," *Int. J. Electr. Power Energy Syst.*, vol. 49, pp. 104–113, Jul. 2013.

[47] A. C. Rueda-Medina and A. Padilha-Feltrin, "Distributed generators as providers of reactive power support—A market approach," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 490–502, Feb. 2013.

[48] A. Samimi, A. Kazemi, and P. Siano, "Economic-environmental active and reactive power scheduling of modern distribution systems in presence of wind generations: A distribution market-based approach," *Energy Convers. Manage.*, vol. 106, pp. 495–509, Dec. 2015.

[49] J. Lin, L. Gan, and E. Foruzan, "Towards a voltage regulation market," in *Proc. 48th North Amer. Power Symp. (NAPS)*, D. W. Gao, Ed. Piscataway, NJ, USA: IEEE, Sep. 2016, pp. 1–6.

[50] S. B. Raha, K. K. Mandal, and N. Chakraborty, "Pareto-efficient double auction power transactions for economic reactive power dispatch," *Appl. Energy*, vol. 168, pp. 610–627, Apr. 2016.

[51] A. Khandani and A. A. Foroud, "Design of reactive power and reactive power reserve market," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 6, pp. 1443–1452, Apr. 2017.

[52] A. Ahmadimanesh and M. Kalantar, "A novel cost reducing reactive power market structure for modifying mandatory generation regions of producers," *Energy Policy*, vol. 108, pp. 702–711, Sep. 2017.

[53] J. P. Roselyn, D. Devaraj, and S. S. Dash, "Voltage-based reactive power pricing in deregulated environment using hybrid multi-objective particle swarm optimisation," *Int. J. Ambient Energy*, vol. 39, no. 3, pp. 285–296, Apr. 2018.

[54] E. Sahraie, A. H. Marzouni, A. Zakariazadeh, and M. Gholami, "New reactive power market clearing scheme with controlling the market competitive level," in *Proc. Int. Power Syst. Conf.*, Teheran, Iran, 2018, pp. 1–8.

[55] D. Jay and K. S. Swarup, "Locational marginal pricing of reactive power in real time market considering voltage support requirement," in *Proc. 9th Int. Conf. Power Energy Syst. (ICPES)*. Piscataway, NJ, USA: IEEE, Dec. 2019, pp. 1–6.

[56] M. Toulabi and A. Samimi, "Reliability based reactive power and reserve market modeling considering uncertainty on units outages," *Electr. Power Compon. Syst.*, vol. 48, nos. 12–13, pp. 1250–1262, Aug. 2020.

[57] M. N. Mojdehi, M. Fardad, and P. Ghosh, "Technical and economical evaluation of reactive power service from aggregated EVs," *Electr. Power Syst. Res.*, vol. 133, pp. 132–141, Apr. 2016.

[58] E. Sahraie, A. Zakariazadeh, and M. Gholami, "Development of a multi-objective framework for the separate active and reactive power market clearing with index-based vision," *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 5, May 2020, Art. no. e12318.

[59] B. Tamimi, C. A. Canizares, and S. Vaez-Zadeh, "Effect of reactive power limit modeling on maximum system loading and active and reactive power markets," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 1106–1116, May 2010.

[60] K. S. H. Beagam, R. Jayashree, and M. A. Khan, "A new DC power flow model for Q flow analysis for use in reactive power market," *Eng. Sci. Technol., Int. J.*, vol. 20, no. 2, pp. 721–729, Apr. 2017.

[61] A. J. von Appen, B. C. Marnay, C. M. Stadler, D. I. Momber, E. D. Klapp, and F. A. von Scheven, "Assessment of the economic potential of microgrids for reactive power supply," in *Proc. 8th Int. Conf. Power Electron. (ECCE Asia)*, May 2011, pp. 809–816.

[62] T. Kumano and M. Kimiduka, "Collaborative reactive power control of photovoltaic power generation systems in a future distribution network based on reactive power price," *IFAC Proc. Volumes*, vol. 45, no. 21, pp. 512–517, 2012.

[63] A. Koide, T. Tsuji, T. Oyama, T. Hashiguchi, T. Goda, T. Shinji, and S. Tsujita, "Real-time pricing of reactive power in the voltage profile control method of a future distribution network," *Electr. Eng. Jpn.*, vol. 187, no. 1, pp. 1–15, Apr. 2014.

[64] D. Jay and K. S. Swarup, "Game theoretical approach to novel reactive power ancillary service market mechanism," *IEEE Trans. Power Syst.*, vol. 36, no. 2, pp. 1298–1308, Mar. 2021.

[65] F. Hinz and D. Most, "Techno-economic evaluation of 110 kV grid reactive power support for the transmission grid," *IEEE Trans. Power Syst.*, vol. 33, no. 5, pp. 4809–4818, Sep. 2018.

[66] H. Gerard, E. Rivero, and D. Six. (2016). *Basic Schemes for TSO-DSO Coordination and Ancillary Services Provision: D1.3*. [Online]. Available: http://smartnet-project.eu/wp-content/uploads/2016/12/D1.3_20161202_V1.0.pdf

[67] E. Hillberg, A. Zegers, B. Herndler, S. Wong, J. Pompee, J.-Y. Boumaud, S. Lehnhoff, G. Migliavacca, K. Uhlen, I. Oleinikova, H. Pihl, M. Norström, M. Persson, J. Rossi, and G. Beccuti, "Flexibility needs in the future power system: Discussion paper," ISGAN, ISGAN Annex 6 Power TD Syst., Tech. Rep., 2019. [Online]. Available: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2595775/ISGAN_DiscussionPaper_Flexibility_Needs_In_Future_Power_Systems_2019_v01.pdf?sequence=1

[68] M. Doostizadeh and M. Ettehadi, "A new procedure for reactive power market clearing considering distributed energy resources," *Int. J. Eng.*, vol. 32, no. 8, pp. 1134–1143, Aug. 2019.

[69] D. Pudjianto, P. Djapic, G. Strbac, B. Stojkovska, A. R. Ahmadi, and I. Martinez, "Integration of distributed reactive power sources through virtual power plant to provide voltage control to transmission network," in *Proc. CIRED Conf.* Madrid, Spain: AIM, 2019, Paper 2055.

[70] K. Tang, R. Fang, L. Wang, J. Li, S. Dong, and Y. Song, "Reactive power provision for voltage support activating flexibility of active distribution networks via a TSO-DSO interactive mechanism," in *Proc. IEEE Innov. Smart Grid Technol. Asia (ISGT Asia)*. Piscataway, NJ, USA: IEEE, May 2019, pp. 116–121.

[71] F. Retorta, J. Aguiar, I. Rezende, J. Villar, and B. Silva, “Local market for TSO and DSO reactive power provision using DSO grid resources,” *Energies*, vol. 13, no. 13, p. 3442, Jul. 2020.

[72] S. P. Karthikeyan, I. J. Raglend, and D. P. Kothari, “A review on market power in deregulated electricity market,” *Int. J. Electr. Power Energy Syst.*, vol. 48, pp. 139–147, Jun. 2013.

[73] E. Lakic, T. Medved, J. Zupancic, and A. F. Gubina, “The review of market power detection tools in organised electricity markets,” in *Proc. 14th Int. Conf. Eur. Energy Market (EEM)*, Jun. 2017, pp. 1–6.

[74] F. L. Alvarado and T. Overbye, “Measuring reactive market power,” in *Proc. IEEE Power Eng. Soc.*, vol. 1. Piscataway, NJ, USA: IEEE, Jan./Feb. 1999, pp. 294–296.

[75] G. Chicco, “A new method for reactive market power assessment in competitive electricity markets,” in *Proc. 12th IEEE Medit. Electrotech. Conf.*, May 2004, pp. 1061–1064.

[76] F. M. Scherer, *Industrial Market Structure and Economic Performance*, 2nd ed. Boston, MA, USA: Houghton Mifflin, 1980.

[77] A. C. Z. de Souza, F. Alvarado, and M. Glavic, “The effect of loading on reactive market power,” in *Proc. 34th Annu. Hawaii Int. Conf. Syst. Sci.* R. H. Sprague, Ed. Los Alamitos, CA, USA: IEEE Computer Society, 2001, p. 5.

[78] L. de Mello Honorio, A. C. Z. de Souza, J. W. M. de Lima, G. L. Torres, and F. Alvarado, “Exercising reactive market power through sensitivity studies and HHI,” in *Proc. IEEE Power Eng. Soc. Winter Meeting. Conf.*, Piscataway, NJ, USA: IEEE, Jan. 2002, pp. 447–451.

[79] D. Feng, J. Zhong, and D. Gan, “Reactive market power analysis using must-run indices,” *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 755–765, May 2008.

[80] H. Oh and R. J. Thomas, “Real and reactive power prices and market power,” in *Proc. IEEE Power Eng. Soc. Gen. Meeting*. Piscataway, NJ, USA: IEEE Service Center, Jun. 2007, pp. 1–8.

[81] P. Chitkara, J. Zhong, and K. Bhattacharya, “Oligopolistic competition of gencos in reactive power ancillary service provisions,” *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1256–1265, Aug. 2009.

[82] R. R. Samii, S. Nourizadeh, and A. M. Ranjbar, “Strategy deviation index as a new reactive market power indicator,” in *Proc. 7th Medit. Conf. Exhib. Power Gener., Transmiss., Distrib. Energy Convers. (MedPower)*, 2010, p. 212.

[83] S. Soleymani, “Nash equilibrium strategies of generating companies (gencos) in the simultaneous operation of active and reactive power market, with considering voltage stability margin,” *Energy Convers. Manage.*, vol. 65, pp. 292–298, Jan. 2013.

[84] J. Zhang, T. Zhao, W. Liu, Q. Tang, and D. Zheng, “Voltage regulation for active distribution network: A generalized Nash game approach,” in *Proc. IEEE Eindhoven PowerTech*, Jun. 2015, pp. 1–5.

[85] J. Patel, D. Jay, B. Ravindran, and K. S. Swarup, “Neural fitted Q iteration based optimal bidding strategy in real time reactive power market_1,” 2021, *arXiv:2101.02456*.

[86] T. Wolgast, E. M. Veith, and A. Nieße, “Towards reinforcement learning for vulnerability analysis in power-economic systems,” *Energy Informat.*, vol. 4, no. S3, Sep. 2021.

[87] K. Sirvio, L. Valkkila, H. Laaksonen, K. Kauhaniemi, and A. Rajala, “Prospects and costs for reactive power control in Sundom smart grid,” in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT-Europe)*. Piscataway, NJ, USA: IEEE, Oct. 2018, pp. 1–6.

[88] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, “A survey of frequency and voltage control ancillary services—Part II: Economic features,” *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 358–366, Feb. 2007.

[89] K. L. Anaya and M. G. Pollitt, “Reactive power procurement: A review of current trends,” *Appl. Energy*, vol. 270, Jul. 2020, Art. no. 114939.

[90] O. Brückl, M. Haslbeck, M. Riederer, C. Adelt, J. Eller, F. Habler, T. Sator, T. Sippenauer, B. Strohmayer, and J. Stuber. (2016). *Zukünftige Bereitstellung von Blindleistung und Anderen Maßnahmen für die Netzsicherheit*. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/zukuenftige-bereitstellung-von-blindleistung-und-anderen-massnahmen-fuer-die-netzsicherheit.pdf?__blob=publicationFile&v=14

[91] J. Merino, I. Gómez, E. Turienzo, C. Madina, I. Cobelo, A. Morch, H. Saele, K. Verpoorten, E. Rivero Puente, S. Häninnen, P. Koponen, C. Evens, N. Helistö, A. Zani, and D. Siface. (2016). *Ancillary Service Provision by RES and DSM Connected at Distribution Level in the Future Power System*. [Online]. Available: http://smartnet-project.eu/wp-content/uploads/2016/12/D1-1_20161220_V1.0.pdf

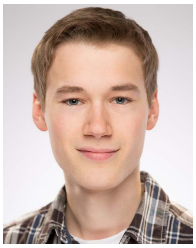
[92] C. Peeters. (2016). *Stabilising Grid Voltage Levels by Generating or Absorbing Reactive Energy*. [Online]. Available: http://www.elia.be/%7E/media/files/Elia/Products-and-services/ProductSheets/S-Ondersteuning-net/S6_EN_2016.pdf

[93] G. Migliavacca, M. Rossi, D. Six, M. Džamarija, S. Horsmanheimo, C. Madina, I. Kockar, and J. M. Morales, “SmartNet: H2020 project analysing TSO–DSO interaction to enable ancillary services provision from distribution networks,” *CIRED, Open Access Proc. J.*, vol. 2017, no. 1, pp. 1998–2002, Oct. 2017.

[94] R. B. Myerson, “Mechanism design,” in *Allocation, Information and Markets*, J. Eatwell, M. Milgate, and P. Newman, Eds. London, U.K.: Palgrave Macmillan, 1989, pp. 191–206.

[95] V. Conitzer and T. Sandholm, “Complexity of mechanism design,” in *Proc. 18th Annu. Conf. Uncertainty Artif. Intell. (UAI)*, Edmonton, AB, Canada, 2002, pp. 103–110.

[96] K. A. McCabe, S. J. Rassenti, and V. L. Smith, “Smart computer-assisted markets,” *Science*, vol. 254, no. 5031, pp. 534–538, Oct. 1991.



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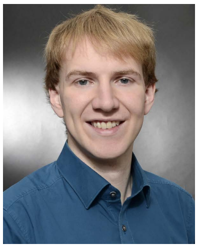

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