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DOI
10.1109/ICDCM.2017.8001028

Publication date
2017

Document Version
Accepted author manuscript

Published in
2017 IEEE Second International Conference on DC Microgrids, ICDCM 2017

Electricity Market Design Requirements for DC Distribution Systems

Longjian Piao*, Mathijs de Weerdt*, Laurens de Vries†
∗Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS)
†Faculty of Technology, Policy and Management (TPM)
Delft University of Technology, Delft, The Netherlands
Email: L.Piao@tudelft.nl, M.M.deWeerdt@tudelft.nl, L.J.deVries@tudelft.nl

***Abstract*—DC distribution systems (DCDS) connect local generators and loads directly. By avoiding unnecessary losses in AC-DC conversion, DCDS offers higher energy efficiency. Since different parties in a DCDS may have conflicting goals, matching between power supply and demand should be done with carefully designed allocation rules and monetary transfers, such that no one prefers to act otherwise than the outcome of the allocation. This paper reveals DCDS' unique operational requirements and indicates the challenges and opportunities they pose to market design. A design framework is introduced into DCDS electricity market, incl. tradable services, design goals, market participants, design options and performance criteria. We review the existing market models for AC and DC distribution systems and point out the direction for future work.**

Keywords—electricity market, market design, DC distribution system, operational requirements, tradable services

NOMENCLATURE

AC	alternating current
BRP	balance responsible party
DAM	day-ahead market
DCDS	DC (direct current) distribution system
DER	distributed energy resource
DSO	distribution system operator
DUoS	distribution use of system
EV	electric vehicle
ICT	information and communications technology
LMP	locational marginal pricing
MG	microgrid
OPF	optimal power flow
PV	photovoltaic
RTM	real-time market
VPP	virtual power plant

I. INTRODUCTION

Developments in ICT and power electronics are changing the power sector. Alongside the increasing use of electronic devices, such as ICT facilities, electric vehicles (EV) and variable-speed drives, many electric loads today have a DC component or directly consume DC power. Meanwhile, central bulk power plants are being replaced by renewable distributed energy resources (DER), especially PV panels and batteries that are operated in DC [1]. However, AC grids are still used to connect these devices, leading to multiple unnecessary AC-DC conversions and accordingly losses.

This work is part of the DC Distribution Smart Grids (DCSmart) project under the European Union's ERA-NET Horizon 2020 Programme.

DC distribution systems (DCDS) couple loads, distributed generators, and storages directly. By avoiding unnecessary conversions, DCDS offers higher energy efficiency. Although DC microgrids and DCDS have been widely studied in recent years, most studies focus on technical issues, incl. feasibility, topology, control, stability and protection [2]. In a DCDS, when energy devices are owned and operated by different parties, one's goal inevitably deviates from the distribution system operator's (DSO) and conflicts with the others' goals. In such cases, central dispatch cannot achieve its goals, if it does not offer customers sufficient incentives to adhere to this dispatch.

A DCDS is different from a DC microgrid (MG) or virtual power plant (VPP) [3]. A MG is a physical energy community, where energy devices are connected through a private network and are operated by a central/distributed control framework. A VPP is a financial energy community, where devices are connected through ICT infrastructure and are operated in a coordinated way. In both cases, the customers share common goals and tend to be cooperative. By contrast, a distribution system does not require cooperative relationships among customers. Therefore, a properly designed market mechanism is required to match power supply and demand, respecting different parties' local decisions.

Several price-based mechanisms have been implemented in AC systems [4]. Time-of-use tariffs and tiered rates are simple and widely used, but they cannot provide sufficient incentives for customers to fine tune their energy consumption. Dynamic pricing (incl. real-time prices set by the local authority), fixes this problem by adjusting energy prices on short notice. However, if congestion happens, it is doubtful that such prices can reflect true generation costs. Locational marginal pricing (LMP), the standard design for the US electricity wholesale markets, gives us a good example of using auctions to balance supply and demand. The idea is to set different nodal prices based on line congestions, then dispatch the cheapest available generators at each node according to the local merit-order. Although LMP is a widely-accepted model in wholesale-level electricity markets, it is not necessarily the most suitable model for distribution-level markets.

Currently, researchers have not yet agreed on the market design methodology in distribution grids, such as flexibility services and distribution use of system (DUoS) tariffs. Further, such market models are designed for AC distribution networks, while the unique operational requirements for DCDS can lead

to very different market designs. With this paper, the authors aim to attract researchers' attention to the economic dispatch of the DCDS, focusing on the short-term scheduling of existing resources. Especially, we study the DCDS' new features that lead to specific challenges in market operation, then outline its market design framework based on these.

The rest of the paper is organized as follows. Sec. II briefly introduces the unique features of the DCDS, then reveals its specific challenges in market design. Sec. III estimates the tradable services needed for DCDS operation, and in Sec. IV we explore how to design a market to trade these services. Finally, Sec. V reviews existing market designs for AC and DC distribution grids, and Sec. VI concludes the paper.

II. Challenges and Opportunities

The unique characteristics of DC pose new challenges to system operation and market design. This section introduces a DCDS' five key differences from AC distribution grids, and indicate the new opportunities they bring to the market design.

A. Direct P-V Coupling

Unlike AC networks where inductance largely decides (active) power flow, line resistance plays the dominant role in a DCDS' power flow [6]. This leads to a direct coupling between power and voltage (P-V). It makes room for straightforward and local control, such as decentralized and voltage-based optimization mechanisms.

In a resistive DC network, sending out (or absorbing) large amounts of power can substantially raise (or lower) the nodal voltage in the area. Therefore, nodal voltage is a key indicator of DCDS operational status, while voltage control should go with power flow optimization and congestion management. However, with power flow control converters, which introduce voltage differences in series with lines, the power flow and voltage can still be controlled independently [7].

B. Low System Inertia

In AC distribution networks, system frequency is coupled to the transmission network through a substation. If a local power mismatch happens, the inertia of all AC generators immediately provides (or absorbs) large amounts of kinetic energy to make up for this local power imbalance, while the system frequency is kept close to its nominal value.

In a DCDS there is no frequency, but the system should be supported to stay close to its nominal voltage. The generation is largely dependent on non-spinning units, such as PV panels and fuel cells. Hence, the system's mechanical inertia is very limited [3]. Unfortunately, DC converters used for substations and DERs have little overload capacity. If a large load appears in a congested network but local generators cannot meet the demand, system voltage will drop very fast and the system will collapse quickly.

Two approaches can improve a DCDS' response to power imbalance (or voltage deviation). The first one is to increase the system inertia by installing synchronverters [3] for power-intense storage systems, such as flywheels or supercapacitors. However, such devices are very costly at present. The other approach is to avoid the problem by coordinating customer behavior, especially when their power causes line congestions. This approach avoids large investments, but requires real-time coordination between customers and affects their comfort or interests. In this regard, we need real-time trading of power balancing capacity, either with a real-time energy market (up to milliseconds) or with a newly defined ancillary service that deals with this issue. Nevertheless, the DSO should still reserve some balancing capacity to maintain security margin, in order to settle market mismatches ex post. Meanwhile, a network code is needed to regulate prosumer's autonomous operation.

Although new features of DC pose challenges to system operation, they also make room for operational flexibility. Below we will introduce the DCDS' two other features, i.e. broader controllability and faster response, which create new market opportunities for a DCDS.

C. Fewer Conversions, Faster Response

A main advantage of DCDS is the fewer conversion steps between PV panels, batteries, and electronic devices, as indicated in [5] (see Fig. 1). With DC distribution, AC-DC converters and their complex control are avoided. Variable-speed drives (VSD) and wind turbines are operated in AC, but their frequency differs from AC system frequency. In order to integrate them into an AC network, frequency conversion (AC-DC-AC) is still required. In both cases, DC distribution can reduce at least one conversion step where synchronization control is needed (which generally takes one AC period); hence, a DCDS can respond faster to system dispatches.

D. Power Electronics and Flexibility

Many DC devices are interfaced with power electronics, which provide the devices with more flexible operation modes and a broader controllability. For instance, such devices can consume constant power at a wide range of voltage, or adjust power input (output) within milliseconds. This further allows the devices to respond to real-time markets faster. However, to achieve system security and high efficiency, the operation of multiple converters must be coordinated, either using central dispatch or distributed approaches such as droop control. Numerous control strategies are found in [1], which can serve as the technical framework for energy trading.

Although fast and flexible DCDS operation creates new markets opportunities, to dispatch a DCDS economically, we still need to solve optimal power flow (OPF) problem for each dispatching interval. In this regard, DCDS provides another great feature for energy trading, i.e. exact power flow.

E. Exact Power Flow

In steady-state, the power flow on a DC line is expressed by the nodal voltage on its both ends, as shown in (1):

$$P_{mn} = G_{mn} \cdot U_m (U_m - U_n) \text{ , } \forall\, m, n \in N \tag{1}$$

where G_{mn} is the line conductance between node m and n; U_m and U_n are the voltage at these nodes. This power flow is exact because losses are considered ($P_{mn} \neq P_{nm}$ and the difference between them indicates power losses). With (1), DC power flow can be solely represented by voltage magnitudes with

quadratic terms; therefore, the OPF problem for a DCDS can be solved using quadratically constrained programming. Apparently, market mechanisms based on (1) will be more accurate than the mechanisms for AC grids.

Above we listed a DCDS' key features that change its market design. In Section III, we will explore how we turn these features into market opportunities, and explicitly define tradable services before designing a market for each of them.

III. Services to Trade

The aforementioned DCDS' features will bring specific challenges to market design. However, it is unclear if a DCDS' technical function should be provided by the system operator, or it should be traded in the local market. In this section, we distinguish the services that are tradable in a DCDS, then investigate the advantages and disadvantages they bring to the electricity market. Table 1 reviews the general requirements for DCDS operation, from power balancing to various ancillary services [1][2][7][8][9], then evaluates their tradability in terms of participation, exchangeability, and cost-causality.

The primary goal of the DCDS system is to balance power supply and demand. With weather forecast and historic load profile, it is possible to predict load and renewable generation in a day-ahead manner. Based on this, local customers can optimize their power prosumption by running the cheapest generators for each dispatch interval, for instance based on day-ahead market (DAM) clearing results. However, since both generation and load are stochastic, a great challenge is to design a DAM that reduces uncertainty in power scheduling.

Due to uncertainty in generation and consumption, real-time power dispatch is inevitably different from the day-ahead schedule. To maintain power balance in real-time, prosumers can reschedule their operation to make up for the imbalance, for instance based on a real-time market (RTM). In both DAM and RTM, all willing prosumers are involved in energy trading, which is by nature cost-causal (generation cost) and highly exchangeable (little loss). Apparently, electrical energy is the fundamental tradable service in the DCDS operation.

Although energy supply is the fundamental function of a DCDS, it has to be supported by ancillary services. Ancillary services help to maintain the reliable operation of power systems, which is required for delivering power from seller to purchaser [10]. At AC wholesale level, ancillary services, incl. frequency regulation and reserve capacity, are traded among generation companies, which helps to maintain the system operation at the lowest cost. For DC distribution, however, the concept of ancillary services still lacks definition. To close this research gap, this paper will summarize DCDS ancillary services and estimate their tradability.

To compensate power imbalances, a DSO must guarantee that there is enough flexibility for real-time power dispatch. It can be a proper amount of operational reserve capacity for the settlement of real-time power imbalances. Though such service is at the cost of flexibility providers' interests, other prosumers are not paying for it so the cost-causality is low. To exploit DER's potential in providing ancillary services [11], the DSO should incentivize flexibility providers, for instance by using day-ahead auctions to ensure operational reserve capacity.

To maintain system security, A DCDS must satisfy power and voltage constraints. As stated in Sec. II, since nodal voltage is directly coupled to power, voltage regulation and congestion management cannot run separately as in AC. Line volume under congestion is exchangeable among prosumers and they should coordinate the use this volume. To mitigate voltage drops and line congestion, energy pricing should be based on locational differences (causing congestion revenues), so that all customers implicitly buy line volume alongside energy trading. In various market models, congestion revenues are allocated differently among DERs (incentive for new generation volume) and the DSO (reinforcement of the congested lines).

Reliability is another major concern for DCDS customers, but highly reliable energy supply requires huge investments in redundant system capacity and islanding services. However, reliability is a public good to all DCDS customers and it is only exchangeable among customers upon contingency, for instance during congestion or islanding. To turn this public good into a cost-causal service, reliability-based DUoS tariff can be considered. Under this tariff, users with higher reliability requirements need to pay more, but their connection will be guaranteed first in case of contingency. As reliability needs a long-term assessment, this tariff can be fixed on a yearly basis.

Table 1 Tradable Services in DC Distribution Systems

Operational requirements	Tradable service	Participation	Exchangeability	Cost-causality	Tradability	Trading horizon
Real-time power balancing	Electrical energy	All customers	High	High	High	Real-time
Day-ahead power scheduling	Electrical energy	All customers	High	High	High	Day-ahead
Real-time dispatch flexibility	Operational reserve	Flexible prosumers	Medium	Low	Medium	Day-ahead
Voltage regulation	Line volume	All customers	High	Medium	High	Real-time
Congestion management						
Reliability upon contingency	Reliability-based DUoS	All customers	Medium	Low	Low	Yearly
Safety, protection, power quality	N/A	Few customers	Very low	Very low	Very low	N/A

Finally, safety, protection, and power quality also play an important role in the operation of a DCDS. Due to technical complexity, such services cannot be provided by individual end customers, so the responsibility still lies with the DSO. Nevertheless, network codes should apply to DC electric devices, so that they satisfy the minimum requirements for secure DCDS operation.

Based on the tradability and trading horizon in Table 1, the aforementioned tradable services are further categorized in four groups, i.e. power scheduling, power balancing, real-time ancillary services (incl. voltage regulation and congestion management) and other ancillary services. Based on the trading horizon, we propose an initial market framework for DCDS, where the above tradable services are respectively traded in RTMs, DAMs, or through yearly contracts, as shown in Fig. 1. Our aim is to design a short-term market framework for DCDS; therefore, in the following sections we will focus on the services traded in day-ahead and real-time markets, i.e. energy trading, operational reserve, voltage regulation and congestion management.

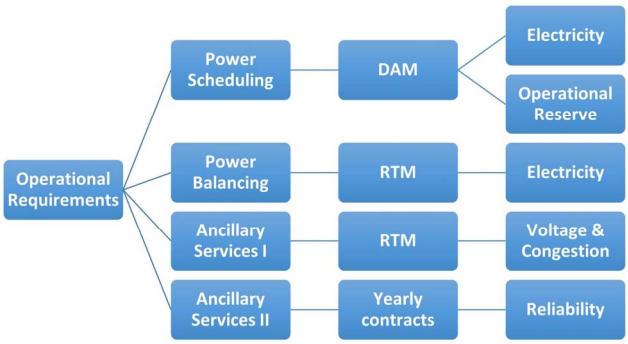

Fig. 1. *Time Horizons of DCDS Tradable Services*

IV. Market Design Framework

In this section, we will develop a framework for DCDS market design, including design goals, market participants, design options and performance criteria.

In 2015, the European Commission carried out a survey on the current electricity market design [12]; the public concerns related to distribution-level markets are listed below. First, pricing schemes should reflect scarcity, but the lack of dynamic pricing is preventing the integration of demand response in retail markets. End-user energy tariffs do not respond to the dynamic wholesale energy prices, nor do they consider the status of local power balance. Second, there is no locational difference in the current market mechanisms, while increasing loads and DERs are causing network congestions. Third, the existing market models are not designed for renewable source integration. Hence, full balancing obligations and phasing-out of public support schemes are major challenges for renewables. Although the concerns stem from AC market operation, similar problems are foreseen in DCDS markets. To avoid these problems starting from the design phase, we will outline a market design framework for DCDS, using the same method described in [13] and [14].

A. Design Goals

The fundamental task for a DCDS electricity market is to dispatch local generation resources at the minimum cost. However, to meet the specific challenges in the operation of distribution grids, following design principles are suggested by the literature.

Open Access [15]. It enables the inclusion of small DERs and prosumers (smart homes, EVs) in the market.

System support. The market outcome must stay within system constraints; it should also improve system performance, such as energy efficiency [16] and system security [17].

Efficient Allocation [16], incl. productive (use the cheapest resources) and allocative efficiency (allocate them to the ones that value them the most) [15].

Competitiveness [17]. Due to limited players, competition among local DERs is not comparable to wholesale market. To avoid market power abuse, market mechanisms should provide better competitiveness among customers.

Stable, Predictable, Effective Price [15]. Electricity price should reflect locational and temporal power scarcity, but it should also stay within the customers' acceptable range.

Transparency [16]. System operational status and market clearing results should be open to all customers, which reduces information asymmetry.

Cost-causality [15]. Customers should be paid/rewarded for their own contribution to public goods and services.

Decarbonization [17]. Clean, renewable DERs need to be dispatched in priority and the intermittent generation should be supported by flexibility services.

Social acceptance [16]. A market design needs to be simple in theory and fair among customers [15]. It should be budget-balanced so that there is no fiscal imbalance when it is cleared.

Scalability [7]: To serve more customers in a regional DCDS, the market design should be efficient in computation and communication. Decentralized mechanisms are preferred.

Cost Recovery [15]. DSO and producer's revenue should cover their investments and fixed costs in the long run.

Future Investment Signaling [16]. The market should indicate new investors to invest in the desired technology, and place their assets at desired locations.

Nevertheless, some principles are contradictory in practice, such as allocative efficiency and customer fairness. Hence, market designers need to compromise on the design principles.

B. Market Participants

After defining the design goals, participant modeling is the second step of market design. In a DCDS, it starts with the smallest market entity—prosumer. A prosumer can represent a single household (serving as a nanogrid), a small shop or a private EV, which is 1) operated by one decision maker, and 2) is equipped with a separate smart meter. In this sense, pure loads, distributed generators and storage systems can also be seen as partial prosumers, so long as they meet these criteria.

A prosumer has its own goals and interests. Prosumers with common goals can create an energy community, such as a MG or a VPP [18]. Within this community market, information is mostly shared and prosumers tend to trust each other and cooperate in energy production and consumption. However, in a distribution system such as a DCDS, prosumers become more self-interested and cooperation is hardly possible. Therefore, single prosumers, VPPs and MGs in a DCDS need to trade energy with each other through the local market. Finally, the regional DCDS is connected to the transmission network and trades energy with the wholesale market. Fig. 2 illustrates the relationship between DCDS markets at different layers and indicates their correspondence from the technical perspective.

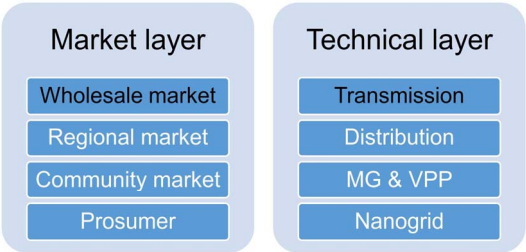

Fig. 2. *Layers in a DCDS Electricity Market*

C. Design Options

To design a market with desired outcomes, one needs to make choices among the design options. For each tradable service, the following design options should be considered when designing an auction, suggested by on [13] and [14].

Bidding parties: defines if an auction is unilateral (only suppliers bid) or bilateral (both supply and demand side bid).

Bid information: including quantity, quality, price, bidder constraints and time of delivery.

Trading horizon: determines if a market needs to be cleared before delivery (ex ante) or afterward (ex post). In a short-term energy markets, ex ante clearing can be day-ahead, hour-ahead, or minute-ahead.

Trading interval: depends on the desired time resolution of the delivery, which can be per day, per hour, or per minute.

Optimization problem: the objective function of a market, such as min. generation costs or min. loss of load probability.

Constraints: incl. Kirchhoff Current Law, prosumer output constraints, line constraints, nodal voltage constraints, ramping constraints, and other customer-related constraints.

Mechanism: centralized mechanisms such as call auction and continuous auction, or decentralized mechanisms such as direct (peer-to-peer) trading.

Time steps: decides if the optimization is continuous or discrete. For optimal dispatch of storage systems, dispatch should be based on multiple discrete time steps.

Decision making: decides if the optimization is solved in a deterministic or stochastic manner (with weather scenarios).

Pricing: determines which price the winning bidders need to pay and whether they are paid the same (uniform-price, marginal pricing) or differently (discriminatory, pay-as-bid).

Technology neutrality: whether one technology is preferred or has priority over another. For instance, subsidies can be given to renewables and storage systems.

Last but not the least, a market needs to have a *Rule for Settlement,* which makes up the mismatch in the trading and the actual delivery ex post.

D. Performance Criteria

Above we have outlined the key elements in the market design for a DCDS. Finally, to examine whether a market design reaches its design goals, we need to review its attributes and evaluate its performance in practice, either by on-site case studies or by simulations. In 2003, Zhou [19] proposed a benchmarking rule for major AC wholesale markets in the US. By applying this framework to our design goals, we propose performance criteria to benchmark different DCDS market designs, as shown in TABLE 2.

TABLE 2 DESIGN GOALS AND PERFORMANCE CRITERIA

Design goals	Performance criteria
Open access to customers	Bidding parties, requirements for new prosumers
Support to technical operation	Voltage fluctuation, OPF, energy losses, volume of operational reserve, loss-of-load probability
Efficient allocation	Total producer surplus and total consumer surplus;
Competitiveness	Concentration ratio (HHI index), market power (Lerner index), market liquidity
Stable, predictable, effective price	Load-weighted average energy price, ancillary service price, demand-side participation rate
Transparency	Information disclosure pre-trade and after the market clearing, information asymmetry
Cost-causality	Payment scheme based on one's own contribution
Decarbonization	Priority and subsidy towards renewables, flexible services for renewable energy integration
Scalability	Requirements for computation and communication, decentralized mechanisms
Social acceptance	Simplicity and fairness among customers (minimal satisfaction), budget balance
Cost recovery	Net revenue of the DSO and DER
Future investment signaling	Total congestion revenue, technology neutrality

V. EXISTING MARKET DESIGNS

Electricity trading is a typical application case in the market design. It is a combinatorial auction of multiple generation resources under a set of strict constraints. Due to lack of storage capacity, electricity supply and demand must be balanced in real-time at every node, while satisfying the operational constraints of the power network.

In the past decades, developments in electricity market design have been focusing on the wholesale-level and locational marginal pricing (nodal or zonal) has become the standard design for wholesale electricity markets. However,

distribution-level power systems remain a natural monopoly—though some effort in retail competition—and energy payments are largely based on fixed tariff and time-of-use tariffs. As suggested in [20], future tasks for DSOs should include better integration of renewable energy and demand-side response, following the non-discriminatory and market-based pricing principles in system dispatch. Especially, the price for power imbalance should be based on the real-time value of energy. For instance, as stated in [15], a DER's additional impact to the distribution network (positive or negative) can be allocated to its owners, through cost-causal allocation mechanisms. Below we review some existing works on distribution-level electricity market design, pointing out their highlights and limitations.

A. Distribution-level Market Design

In 2005, OFGEM, the British government regulator for gas and electricity, published a framework for distribution network pricing [16], stressing the influence of distributed generation. According to the framework, the main objective is to improve *economic efficiency*, by sending price signals to network users based on the costs these users impose on network operation and expansion. The second objective is to *recover DSO's allowed revenues*, while network pricing should be reasonably stable and predictable.

To mitigate local grid congestions, Rasmussen et al. [21] propose three market models for distribution grids based on different tariff structures. The first market works in a *bid-less day-ahead* manner, which is simple in principle and easy to implement. However, due to lack of real-time control, no real-time adjustment can be made, either. The second market is based on *real-time bidding*, where every generator needs to submit bids to the market and activates them by the balance responsible parties (BRP). With real-time measurements from end-users, this market can be cleared more accurately and it is less dependent on forecasts. However, to real-time bidding requires extensive communication and high transaction costs. In comparison, the third one is also based on real-time, but no bid is required. Instead, the DSO sends a tariff signal to customers, which leads their prosuming behavior towards the desired effect. This design shares many benefits with the second one, but the DSO must forecast supply and demand before the delivery, and decide an optimal energy price for the tariff signal. It is noted that in all the three cases, end-users are not requested to submit load schedules since it is considered unrealistic for small customers to schedule their loads. This affects end users' motivation to respond to real-time balancing. Instead, the authors suggest that load forecasts should be done by a BRP based on historical demand, price information, and weather forecasts. However, as individual consumers' load patterns are highly stochastic, load prediction will be more challenging and error prone at the distribution level, compared to wholesale-level prediction where loads are well aggregated.

B. Market Designs for DC Distribution

Compared to AC, only a few papers discussed the price-based optimal dispatch in a DCDS. Below we briefly introduce these papers and discuss their merits and drawbacks.

To formulate the optimization function, Gan and Low [6] study the OPF problem in a DCDS and later solve it using second-order cone programming (SOCP) relaxation. They prove that if voltage upper bounds do not bind, the SOCP relaxation is exact and has at most one optimal solution. Further, Li et al. [22] study OPF problem for DC microgrids under a real-time pricing scheme. The model aims to achieve system cost-efficiency, where each generator is modeled in terms of various operational costs. To achieve higher accuracy and faster response, droop control is implemented in each grid-forming converter, where optimal droop parameters are directly applied to the local level control. However, the allocation efficiency depends on how the parameters are adjusted.

To determine consumer energy prices in a cost-causal way, Asad and Kazemi [23] use the concept of real nodal price to determine energy payments in a DCDS. The idea is to charge customers according to their energy consumption using LMP, plus the marginal losses that they impose. The model is highlighted by its budget-balanced feature and its application in meshed DCDS. The model guarantees productive efficiency and deals with congestions effectively, and the use of LMP helps the model to meet most of the performance criteria stated in Table 2. However, the limited competition in a DCDS can lead to strategic biddings on congestion-prone branches.

To achieve optimal demand response, Mohsenian-Rad and Davoudi [24] present a control framework for DCDS with both centralized and decentralized mechanisms. In the latter, price-based mechanism, a user's objective function consists of three parts, namely the user's utility, the incentive for voltage regulation, and the incentive for fairness enforcement. This model gives customers an extra incentive to provide ancillary services. However, the model does not include the payment for distribution losses, while the objective functions need further extensions in order to manage congestions.

The aforementioned papers are mainly focused on unipolar DCDS. The bipolar DCDS, by contrast, can deliver much higher power capacity with the same power cables and are studied recently. To mitigate the impact of asymmetric loading in a bipolar DCDS, Mackay et al [25] present an exact OPF model, where partial congestion lead to nodal price differences between two polarities. However, the nodal price is sensitive to power imbalances and is, therefore, less stable and predictable.

To sum up, the existing works on DCDS energy market aim to reach selected design goals stated in Sec. IV.A, such as economic efficiency, real-time locational balance, cost-causal payments and customer incentives. They provide some insights into the specific design principles for DCDS markets, yet did not provide a larger picture of the top-down market design. Regarding this, a more comprehensive study on market design and auction rules is urgently required for the economic operation of the DCDS.

VI. Conclusion and Future Work

DC distribution grid's unique operational requirements will pose new challenges to the system operation. This paper reviews the system services required for DCDS operation, then investigates the advantages and disadvantages they bring to the electricity market. A design framework is outlined for DCDS electricity markets, where design goals, market participants, design options and performance criteria are briefly discussed.

Finally, we review current studies on distribution-level market design and indicate the need for more comprehensive studies.

Future work on this topic is suggested as follows. Due to the limited scale of a DCDS, the aggregation of energy production and consumption is at a very low level compared to wholesale markets. Both intermittent renewable generation and stochastic load patterns are adding to the uncertainty in power balance, which poses a great challenge to local forecast and prosumer scheduling. Therefore, when designing local energy markets, trading horizon and dispatch intervals should be carefully chosen (for DAM and RTM) to reduce uncertainty at the lowest cost. New auction mechanisms that help improve economic efficiency and avoid strategic biddings should be developed for DCDS energy trading. Meanwhile, guidelines should indicate how the markets at different DCDS levels should be coupled to each other for better coordination.

In terms of ancillary services, future work should further indicate which ancillary services can be provided by individual customers through a market (such as operational reserve capacity) and whether such solutions can lower the DSO's operational costs. Considering the increasing numbers of DERs and EVs, a remaining challenge for DCDS is to serve for more prosumers with existing infrastructure, so as to improve the load factor of the existing network assets and to postpone network reinforcement. When energy neutral homes become popular, the DSOs needs to design new DUoS tariffs that help them recover their network investments. Finally, simple and practical market mechanisms should be soon available for DCDS energy trading, which can be verified and evaluated in demonstrative and commercial DCDS.

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