DISTRIBUTION-LEVEL FLEXIBILITY PROVISION THROUGH SIMULTANEOUS ASCENDING AUCTIONS

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ABSTRACT

A distribution-level Local Flexibility Mechanism (LFM) is proposed that accompanies distribution network charges consisting of two components: a peak coincidence network charge (PCNC) and fixed charge. The PCNC is a forward-looking charge that considers the cost of future network reinforcements required and is allocated to customers according to their contribution during network peak hours. LFM aims to utilize customers' flexibility efficiently while allowing them to hedge against high PCNC. LFM is based on simultaneous ascending auctions, through which customers book their network capacity during critical hours in advance. The framework along with a case study are presented to illustrate the operation of LFM.

NOMENCLATURE

Sets	
N^c	Number of customers
$N^{B,n}$	Number of flexible load blocks for every customer n
N^P	Number of points that form the network price curve
Parameters	
λ^{Inflex}	Willingness to pay of inflexible load block (€/MW)
$\lambda^{flex}_{n,k}$	Willingness to pay flexible load block k for customer n (€/MW)
λ^{net}_{p}	Price of PCNC points (€/MW)
$Q^{Inflex,MAX}_{n}$	Maximum quantity of inflexible load block for customer n (MW)
$Q^{flex,MAX}_{n,k}$	Maximum quantity of flexible load block k for customer n (MW)
$Q^{net,MAX}_{p}$	Maximum quantity of network capacity (MW)
$Load_n$	Total load of customer n (MW)
δ^{flex}_{n}	Flexibility percentage of customer n (%)
Variables	
Q^{Inflex}_{n}	Quantity of inflexible load block for customer n (MW)
$Q^{flex}_{n,k}$	Quantity of flexible load block k for customer n (MW)
Q^{net}_{p}	Quantity of network capacity (MW)

INTRODUCTION

Active management within the distribution network (DN) are currently taking place as Distribution System Operators (DSOs) and regulators depart from the traditional fit-and-forget approaches to more innovative ones that considers involving the demand side to postpone/eliminate network reinforcements, aiming to increase the system's economic efficiency. Customers are incentivized to rationally participate providing flexibility to the network base on the economic signals and financial compensations they receive, which are transmitted either through the network charge design, or through distribution-flexibility markets. The aim of both is to signalize the customers during network critical hours, encouraging them to shift/reduce/increase their loads/injections. Different proposals of each have been discussed in the literature [1]–[6], yet, to the authors knowledge, they were not combined. Although if both designs are well-aligned, great customer response may be guaranteed.

The purpose of this paper is to develop a distribution-level DSO service named Local Flexibility Mechanism (LFM) that coordinates responses from flexible customers to enable DSOs to access the available physical flexibility instead of continue investing in additional network resources, as it happens under the paradigm of passive network operation. It aims to maximize the value of flexibility, employing it in a way that enhances the system's total economic efficiency. LFM accompanies DN charges as shown in Figure 1. It aligns with economics signals established through DN charges to ensure optimal reactions are conducted from the customers' side, as well as efficient network reinforcement decisions are executed from the DSO's side.

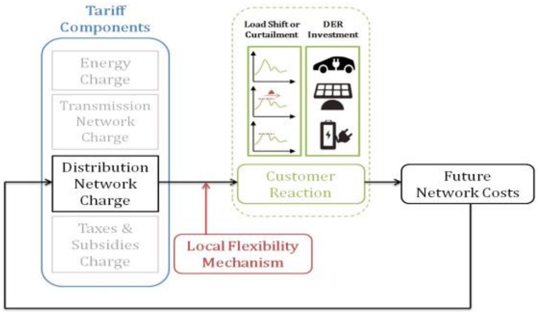

Figure 1 Local Flexibility Mechanism to Enhance Customer Response

The DN charge design considered in this paper is based on the proposal in [7], which consists of fixed charges and forward-looking Peak Coincidence Network Charges (PCNC). PCNC (€/kW) is allocated to customers according to their contribution during network peak hours which are identified based on a pre-defined preventive threshold. Through PCNC, economic signals are transmitted to customers reflecting the incremental cost of required future network reinforcements. At the end of the billing period, ex-post, PCNCs are allocated to customers according to their measured contribution to the peak hours of the elapsed period. Customers may receive estimated information regarding peak hours ex-ante, however the realized peak remains uncertain and depends on the realized power flows. Based on the revenues collected through PCNC, the residual (remaining) network cost is allocated to customers through fixed charges.

Although PCNC sends efficient economic signals, yet it holds high uncertainty to customers since charges are allocated ex-post based on the actual peak hours which may differ that those announced ex-ante. This may happen as customers avoid the expected peak hours and shift their loads creating new unexpected peak hours. Thus, LFM is proposed to on one hand coordinate customers' responses, reducing the probability of new peak hours, and on the other hand uses the economic signals already established through the PCNC to efficiently utilize customers' flexibility. LFM operates differently from distribution-level flexibility markets in the literature in two main aspects: 1- it complements distribution network charges, aligning with its pre-established economic signals, 2- during network critical hours, customers bid to book network capacities in advance to hedge against high PCNC, rather than bidding to provide flexibility services in exchange for financial compensations.

The rest of the paper continues as follow: distribution-level flexibility markets available in the literature are discussed, then the proposed LFM is presented, then a case study is carried out to illustrate how LFM operates, and finally conclusions are highlighted.

DISTRIBUTION-LEVEL FLEXIBILITY MARKET

Distribution level flexibility markets in the literature are referred to as flexibility market [4], [6], [8], micro-market [9]–[11], local market [12]–[14], decentralized market [5], where they all aim to utilize customers' flexibility to relieve network congestion and/or postpone network upgrades. Similar to ancillary services (AS) market developed for TSOs, recent proposals for DSOs offer capacity congestion relieve solutions. In [15] a market framework addressing voltage control in multi-microgrid systems is presented, which is a Var market for MV distribution systems that involves DERs. In addition, different flexibility services, electric vehicles (EVs) can offer in ancillary markets, particularly for the low voltage network, are discussed in the Nikola project [16]. Moreover, within the iPower project [17], the need of a flexibility clearinghouse (FLECH) is discussed. FLECH is meant to facilitate DSOs to announce services and aggregators to bid upon.

Moreover, different market designs were proposed to operate during the network's alert stage, where the DSO has an emerging congestion and willing to procure flexibility for relieving network congestions. A framework for distribution level flexibility market (FM) for congestion management is proposed in [6], [18]. FM operates as a day-ahead market, offering flexibility services to solve potential network congestions. It considers aggregated customer flexibility bids and payback preferences in its decision process. The model is based on two stages: a first flexibility service activation, and then payback effect assessment. Moreover, Regional Flexibility Market (Regioflex) [4] also operates during yellow traffic network status. Regioflex uses market-based mechanisms to avoid critical regional network situations as an alternative to the network expansion. In the yellow phase, the DSO calls for flexibility services when required. Customers and aggregators then offer flexibility options according to their portfolio, and DSOs contract the needed flexibility and compensate the customers. Another local market design is the de-flex-Market model [5]. This model requires customers to sign flexibility contracts. According to the congested assets and flexibility needs, the DSO identifies the size of the aggregated distribution grid area and contacts registered customers within that area. Engaged customers that provide flexibility services are compensated by direct incentive payments. A customer that violates the network restriction requirement is exposed to a non-compliance fee.

Market-based approaches are implemented in order to establish efficient distribution-level coordination. Most of the aforementioned local flexibility markets use auctions to procure or utilize customers' flexibility. Auctions allow an adequate level playing field in which competition is fostered and flexibility services can be provided on competitive basis. However, as earlier mentioned, the discussed proposals are disconnected from the network charge design. Thus, LFM is proposed and discussed in the following section.

PROPOSED LOCAL FLEXIBILITY MECHANISM (LFM)

LFM operates through dynamic auctions: Simultaneous Ascending Auction (SAA) which works as a tool to retrieve information regarding future network usage. The SAA is held during network critical hours to allocate network scarce capacity that is not yet absolute, to reveal customer preferences whether the local network should be upgraded to accommodate extra capacity, or other more economical solutions could be held from the customers' side (such as load shifting or DG dispatching). Dynamic auctions with simultaneous rounds are the most suitable to attain these objectives. They are designed for auctioning multiple units (network capacity) of different products (hours) that act as substitutes for each other simultaneously. Hence, customers are encouraged to shift part of their load or injections to hours that are more economic.

The product to be auctioned is the network's capacity during critical hours which are established by a pre-defined network utilization threshold, and during borderline peak hours where the threshold is relaxed to include also hours with some potential to become peak hours, as shown in Figure 2 (i.e. Hours 19, 20 and 21). The relaxed threshold should be set to guarantee an adequate level of security. The auction is held to offer network capacity for customers to book it in advance. The auctions are held locally; hence, only customers that affect the utilization level of peaking assets will be able to contribute to the auction. Moreover, auctions will be held simultaneously for all peak and borderline peak hours on daily basis where peak hours are expected as in the day-ahead energy market, and the DSO is the auctioneer. Customers can participate in the auctions for multiple hours at the same time, ensuring an optimal schedule for themselves. The auctions aim to signalize customers that load/injections should be shifted away from these hours.

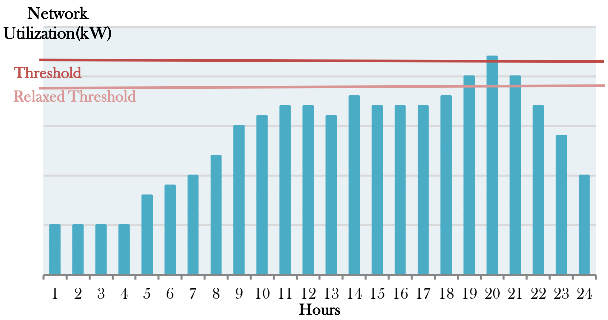

Figure 2 Peak and Borderline Peak Hours Identification

SAA are held locally by the DSO; hence, only customers that affect the utilization level of peaking assets will be able to contribute to the auction. Customers will bid paired capacities and prices, as illustrated in Figure 3, where the bids are arranged in descending order along and matched with the PCNC curve. The PCNC curve presented is composed of two parts, although the authors recognize that other variants are also possible. The first part consists of an exponential relationship for network capacities booked below the threshold. It aims to value the network's capacity progressively, signalizing customers as the threshold is being approached. The second part follows a linear relationship for those capacities exceeding the threshold, based on the PCNC calculation method presented in [7]. The clearing price is then set based on the marginal accepted bid. Customers may also bid with injection quantities (Qi) and prices, which are included within the PCNC's price curve, increasing the network capacity at their corresponding prices as in Figure 3.

Formulation

Equations (1)-(5) present the formulation of the LFM through SAA, where the objective is to maximize the social welfare (SW) as in equation (1) and subject to the constraints (2)-(5). The bidding blocks per customer include both the inflexible and flexible loads. The price for the inflexible load is set equivalent to the PCNC. Whereas the flexible load is divided into several blocks as in (6)-(8) based on the flexibility percentage (δ^{flex}) as proposed in [19]. The price associated with each flexible load block is set randomly within a given range.

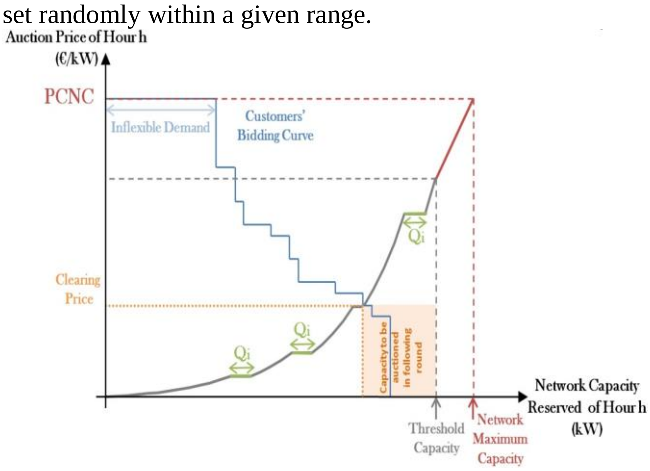

Figure 3 Illustration of simultaneous ascending auction with injection bids

$$\text{Max SW} = \sum_n^{N^c}\Big[\big(\lambda^{\text{Inflex}}\ Q_n^{\text{Inflex}}\big) + \sum_k^{N^{B,n}} \lambda_{n,k}^{\text{flex}}\ Q_{n,k}^{\text{flex}}\Big] - \sum_p^{N^P}\Big[\lambda_p^{\text{net}}\ Q_p^{\text{net}}\Big] \qquad (1)$$

$$0 \le Q_{n,k}^{\text{flex}} \le Q_{n,k}^{\text{flex,MAX}} \qquad \forall n,k \qquad (2)$$

$$0 \le Q_n^{\text{Inflex}} \le Q_{n,k}^{\text{Inflex,MAX}} \qquad \forall n,k \qquad (3)$$

$$0 \le Q_p^{\text{net}} \le Q_p^{\text{net,MAX}} \qquad \forall n,k \qquad (4)$$

$$\sum_n^{N^c}\Big[\big(\lambda^{\text{Inflex}}\ Q_n^{\text{Inflex}}\big) + \sum_k^{N^{B,n}} \lambda_{n,k}^{\text{flex}}\ Q_{n,k}^{\text{flex}}\Big] = \sum_p^{N^P}\Big[\lambda_p^{\text{net}}\ Q_p^{\text{net}}\Big] \qquad (5)$$

$$Q_n^{\text{flex}} = \text{Load}_n \times \delta_n^{\text{flex}} \qquad \forall n \qquad (6)$$

$$\text{Load}_n \le Q_n^{\text{Inflex}} + Q_n^{\text{flex}} \qquad \forall n \qquad (7)$$

$$Q_{n,k}^{\text{flex}} = \frac{Q_n^{\text{flex}}}{N^{B,n}} \qquad \forall n,k \qquad (8)$$

The LFM is a straight forward approach that would assist DSOs managing critical network utilization periods and obtaining flexibility services from customers. A numerical example is provided in the following section to illustrate how the LFM operates using SAA.

CASE STUDY

The case study carried out aims to illustrate the operation of the LFM through SAA. A simple 2-bus distribution network presented in [19] and previously used in [7], [20] is used and illustrated in Figure 4. A distribution network of a 2.5MW capacity is connected to the higher voltage grid and serves several customers that are grouped into four (C1, C2, C3 and C4) and their load profile is shown in Figure 5. The network is expected to accommodate a load increase in the following year of 0.1MW, which requires upgrading the network. The least network reinforcement that could be carried out is 0.5MW, equivalent to 20% of the current network's capacity, thus the equivalent reinforcement cost is assumed to be 20% of the current annual network cost (657,000€). It is assumed that the network's utilization level exceeds the threshold 10% of the year (i.e. 880 hours). This leads to a maximum PCNC of 298.6€/MW at a network capacity of 2.5MW and a minimum PCNC of 239€/MW at the threshold network capacity which is set at 2 MW (80% of network capacity).

The relaxed threshold is set at 1.8MW.

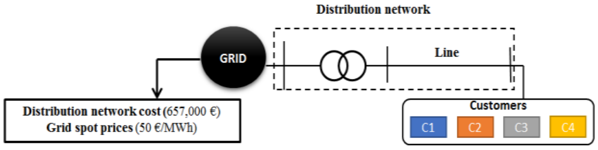

Figure 4 Case study

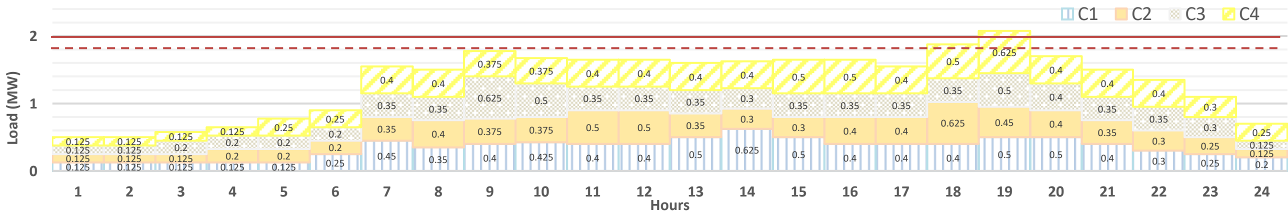

Figure 5 Customers Load Profile

The customers' flexibility percentage (δ^{flex}) are assumed to be 5%, 10%, 15% and 20% for C1, C2, C3 and C4 respectively. For the customers' bids, the range of prices for the first block of flexible load is 150€/MW – 239€/MW (which is the minimum PCNC), for the second block: 100€/MW - 150€/MW, and for the third block: 50€/MW – 100€/MW. The optimization problem was formulated on Matlab using linear programming.

Results & Observations

Based on the threshold and the relaxed threshold, two critical hours were identified: hour 18 which is a borderline peak hour, and hour 19 which is peak hour. Therefore, SAA was held for those two hours and results of the first round are shown in Figure 6 based on the customers' bids presented in Table 1, where the accepted bids are shaded. Customers with unaccepted bids are expected to either bid in the second round for their remaining flexible load with prices greater than the clearing price of the first round, or shift/curtail the remaining flexible load. The available capacity to be auctioned in the second round is that remaining to the threshold (2MW) after the accepted bids of the first round. Since SAA follows uniform pricing, the total cost of the first round is 230€ and 340€ for hours 18 and 19 respectively, which are to be included in the network cost recovery, affecting the fixed charge component of the tariff.

LFM is beneficial to the whole system. Customers are incentivized to participate in the SAA to hedge against the PCNC regardless whether they are flexible or not, since they will be paying the clearing price which is less than the PCNC. Those that do not participate in the auction, or consume more that their booked network capacity, will face the risk of PCNC during real-time if it turns out to be a peak hour. For example, in hour 19, if all customers decide neither to participate in the auction, nor shift their load, they will pay PCNC for the whole load of 2.075 (i.e 620€). Whereas, if they decide to participate and shift part of their load, they will be able to save approximately the half (i.e. 340€). In addition, DSOs receive accurate information regarding the network's utilization level and avoids the creation of new unexpected hours. Overall, the amount paid by the customers multiplied by the number of peak hours (880) is lower than the cost of network reinforcements, leading to higher economic efficiency.

The remaining customers' flexible load may raise a concern. In the case where the customer is not willing to increase the price and participate in the second round, he would be left with the choice to either curtail the load or shift it to earlier or later hours that are not included in the SAA. Consequently, if customers coincidently shift their remaining flexible load to the same hour, a new unexpected peak hour may be realized in real-time. Since customers do not declare their load profiles in advance, such information cannot be foreseen by the DSO. Thus, the relaxed threshold should be well designed to include all potentially peak hours. Although this would increase the number of auctioned hours, yet it will mitigate the occurrence of new peak hours.

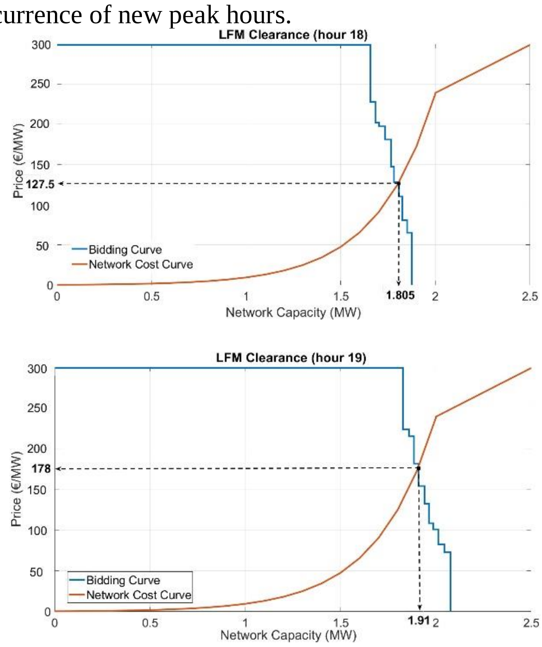

Figure 6 LFM clearance for hours 18 & 19

		Hour 18		Hour 19	
		Q (MW)	λ (€/MW)	Q (MW)	λ (€/MW)
C1	*IF*	0.38	298.6	0.475	298.6
	F	0.02	1974	0.025	225.1
C2	*IF*	0.5625	298.6	0.405	298.6
	F	0.0313	181.2	0.0225	167.3
	F	0.0313	147	0.0225	111.3
C3	*IF*	0.2975	298.6	0.425	298.6
	F	0.0175	227.9	0.025	165.1
	F	0.0175	127.5	0.025	111.4
	F	0.0175	81.1	0.025	71.8
C4	*IF*	0.4	298.6	0.5	298.6
	F	0.025	202.2	0.0313	177.6
	F	0.025	114	0.0313	146.2
	F	0.025	65	0.0313	71.5
	F	0.025	23.6	0.0313	9.3

F: Flexible load, IF: Inflexible load

Table 1: Customers' bids during critical hours

CONCLUSION

The proposed LFM aims to efficiently extract and utilize customers' flexibility based on pre-established economic signals through the PCNC. In addition, it allows customers to hedge against the PCNC, reducing the uncertainty of peak hours. SAA is efficient in the sense that auctions for critical hours are simultaneously held, allowing customers shift between hours. However, due to the limited number of rounds as the whole capacity could be allocated in the first round, there is not much room for customers to speculate. Moreover, although it is expected that better customer reaction is to be retrieved through LFM compared to flexibility markets in the literature, due to the strong economic signal and customer loss-averse nature, yet, auctions that include several rounds will be more efficient and may also reduce the probability of new unexpected peak hours. Other possible auctions designs may be also explored in future research.

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