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Collaboration Models Between Distribution System Operators and Flexible Prosumers

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ABSTRACT

In power systems with increased penetration of renewable energy resources (RES) additional flexibility is required. Traditionally, conventional power plants used to provide flexibility services to the Transmission System Operator, while the Distribution System Operator (DSO) could not be involved in the service procurement for local voltage control and congestion management. New energy directives highlight the importance of local flexibility provision enabling market participation from different entities, such as aggregators of flexible prosumers under demand response (DR) programs.

The paper models DR programs and different types of relationship between the supplier, aggregator, prosumers, and the DSO looking into their actions and cost under different pricing strategies. Unlike current situation in which the DSO offers only volumetric (either flat or Time-of-Use), capacity based, or lump-sum based distribution network charges to induce flexible behavior, the main novelty of this paper is a proposal of a methodology calculating a unique price signal sent to the final users by the aggregator that reflects both the energy market price and the DSO's requirement for the service provision. The paper models in detail the coordination between different players deciding on the most effective and cost-efficient solutions in providing flexibility services in low-carbon power systems.

Keywords: aggregator, ancillary services, demand response, Distribution System Operator, price signal

NOMENCLATURE

Abbreviations	
AS	Ancillary services
BES	Battery energy storage
CVA	Coordination via Aggregator
DA	Day-Ahead
DER	Distributed Energy Resources
DSA	Direct Service Activation
DSO	Distribution System Operator
PV	Photovoltaic system
RES	Renewable Energy Sources
RT	Real-time
SA	Shiftable appliance
Parameters	
$\mu_t^{p/s}$	Purchasing/selling energy price for final user [€/kWh]
μ_t^{DA}	Day-ahead energy price [€/kWh]
μ^{DSO}	Price for service provision [€/kWh]
μ_t^{B}	Balancing price [€/kWh]
Δt	Time step [*1h*]
P_t^{PV}	PV production [kW]
P_t^{ms}	Must-serve load [kW]
Variables	
P_t^{p}	Extracted power from the grid [kW]
P_t^{s}	Injected power in the grid [kW]
P_t^{ap}	Power of appliance *ap* [kW]
P_t^{DSO}	Provided service [kW]
$P_t^{DA} \cdot \Delta t$	Contracted energy at DA market [kW]
P_t^{B}	Balancing power [kW]
P_t^{ch}	Charging power [kW]
P_t^{dis}	Discharging power [kW]

1. INTRODUCTION

The transition towards low-carbon power system puts the focus on increasing penetration of renewable energy sources (RES) to reduce the harmful effects of greenhouse gas emissions [1]. To maintain the secure and stable system operation, due to their intermittent nature, RES require additional flexibility. In the past, DSO used to manage the distribution grid according to 'Fit-and-forget' approach. The distribution network was planned according to the worst-case scenario which implied network reinforcements and investments in new

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cables, lines, and transformers. This passive approach becomes very expensive and inefficient in power system with high shares of RES. New paradigm called Active Distribution Network Management is based on real-time (RT) monitoring and control, and instead of network reinforcement, it considers providing flexibility services from distributed energy resources (DER). The main issue in this approach lies in determining adequate price signals from the DSO's side to final customers to stimulate their flexible behavior in order to eliminate local voltage problems and congestion in distribution grid. DSOs in European countries provide only volumetric (either flat or Time-of-Use based), capacity based or fixed lump sum distribution network charges which do not properly stimulate flexible behavior [2].

Moreover, roles and the relationship between different entities should be regulated by law, i.e., directly activating flexibility services from the aggregator might results in increased balancing cost for the supplier which has to be renumerated. Several papers focus on dynamic tariff calculated by the DSO which reflects the cost of congestion based on locational marginal pricing (LMP) [3]–[5]. However, LPMs are not used in Europe and the existing literature [5], [6] models an aggregator as a zero-profit entity in charge of flexible appliances of their portfolio. This paper proposes a novel collaboration model between the DSO, aggregator and flexible prosumers putting the focus on detail modelling of final user's flexibility behavior, willingness to provide the service and creation of price signal from the DSO or aggregator stimulating flexible behavior. Unlike existing literature, in our model the aggregator is not a zero-profit market player, aggregator seeks to optimizes a unique price signal which reflects the cost of energy supply and in the same time incentivizes final customers to provide services to the DSO. The main contribution of our paper is to investigate which type of proposed incentives properly stimulate prosumer's flexible behavior and how actions taken from one entity effect the cost of other players:

1. Supplier participates on DA and balancing market and determines the energy-based price component for final users, while the DSO directly controls the battery storage and in return reduces the annual network charges as a compensation for service provision. The supplier faces the balancing cost for the deviation from DA energy schedule due to the provision of AS from final users.

2. The aggregator is in charge of energy supply and aggregation of flexibility potential from the final users for providing AS to the DSO. The price provided from the DSO to the aggregator has to cover increased balancing cost due to the service provision, renumeration cost to the final customers and ensure a profit margin to the aggregator.

2. COORDINATION MODELS

Different approaches and renumeration mechanisms are considered in the literature in flexibility service provision. Demand response programs are divided in two groups: incentive-based and price-based. This paper investigates the relationships between the DSO, the aggregator/supplier and final users focusing on the final user's behavior under the non-zero-profit aggregator.

2.1 Direct service activation (DSA)

In this approach the final user receives the price which contains an energy based component and network charges. Buying price is higher than selling price, while the selling price is exempted from network charges reflecting the real situation in Europe [7], [8]. In direct load control the DSO is allowed to control the operation of battery storage when necessary [9]. Final users enrolled in direct load control in our approach are assumed to receive 10% reduction on the annual cost of network charges.

The cost of final user in this approach is presented with (1):

$$min \sum_{t \in T} (\mu_t^P \cdot P_t^P - \mu_t^S \cdot P_t^S) \cdot \Delta t \quad (1)$$

The first term in (1) represents the cost for energy delivery paid to the supplier on a daily basis, while the second term is the profit from selling excess energy. Total energy requirement in hour *t* is equal to the sum of consumption of all appliances in the household (must serve load as a nonflexible load, battery storage and shiftable appliance) reduced for production from household PV (2).

$$P_t^P - P_t^S = P_t^{ms} + P_t^{ap} - P_t^{PV} + P_t^{ch} - P_t^{dis} \quad (2)$$

On the other hand, the supplier participates in the DA energy market and faces the balancing cost if real-time energy requirements differ from the predicted schedule (3):

$$\max \sum_{t \in T} \sum_{d \in D} [(\mu_t^P \cdot P_t^P - \mu_t^S \cdot P_t^S) - \mu_t^{DA} \cdot P_t^{DA}] \cdot \Delta t - \sum_{t \in T} \mu_t^B \cdot P_t^B \cdot \Delta t \quad (3)$$

The first term in (3) refers to the profit from selling energy to the final customer reduced for the energy cost on DA market, while the second term is the balancing cost which the supplier faces due to the deviation from DA schedule.

2.2 Coordination via aggregator (CVA)

In this approach the aggregator is responsible not only for the aggregation of final prosumers in flexibility service provision, but also for the energy supply. The aggregator sends its DA profile to the DSO. If necessary, the DSO requires the service activation from the aggregator. The aggregator sends the unique price signal to the final user that combines the electricity cost and also the DSO incentive for service provision. The incentive for service provision is calculated in the bilevel optimization and ensures that prosumers willing to provide flexibility service will be better off with the aggregator compared to their traditional contract, while their comfort will stay unchanged. Coordination model between the aggregator and the DSO is shown in Figure 1:

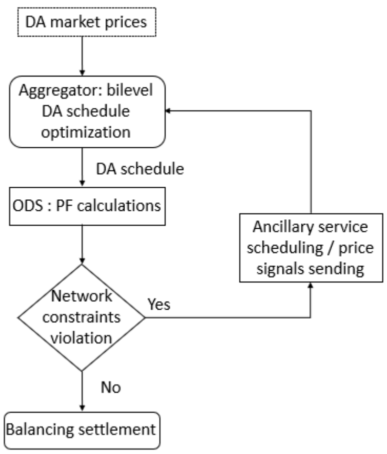

Figure 1 Coordination model between the DSO and the aggregator

Due to the page limitation, the brief structure of the bilevel price determination is given with the upper-level equations (4)-(6) and the lower-level equations (7)-(9):

$$\max \sum_{t\in T}\sum_{d\in D}[(\mu_t^P \cdot P_t^P - \mu_t^S \cdot P_t^S) - \mu_t^{DA} \cdot P_t^{DA}] \cdot \Delta t + \sum_{t\in S} P_t^{DSO} \cdot \mu^{DSO} - \sum_{t\in T} \mu_t^B \cdot P_t^B \cdot \Delta t \quad (4)$$

s.t.

$$f(x) \geq 0 \quad (5)$$

$$g(x) = 0 \quad (6)$$

Profit maximization of the aggregator in (4) is achieved from selling energy to the final users and a compensation from the DSO for the flexibility service provision reduced for the energy cost on DA market and balancing cost. It has to be highlighted that price μ_t^P is a variable representing the unique price for final prosumer which combines both energy component of the price and flexibility service provision. Inequality (5) and equality constraints (6) of upper level gather the consumption profiles of final users and determines the range of μ_t^P price.

Final user minimizes their cost according to the price signals μ_t^P and μ_t^S sent from the aggregator (7). Inequality (8) and equality constraints (9) of lower level represents the model of final user flexible appliances.

$$min \sum_{t\in T}(\mu_t^P \cdot P_t^P - \mu_t^S \cdot P_t^S) \cdot \Delta t \quad (7)$$

s.t.

$$m(x) \geq 0 \quad (8)$$

$$k(x) = 0 \quad (9)$$

Bilevel problem is transformed to the single-level optimization problem with Karush–Kuhn–Tucker (KKT) conditions [10], linearized with Fortuny-Amat Transformations [11] and with big M method.

3. RESULTS

It is assumed that final user is equipped with a battery storage unit (3.4 kW, 4 kWh) and shiftable appliances (P_t^{ap} up to 0.3 kW with total daily consumption 1.6 kWh), while must serve load represents a non-variable load. Different types of final users are modeled: non-home working couple, home-working family, retired couple and students' flat. Their load profiles are generated with [12], while PV production is generated with [13] for two different locations in Denmark. The detail description of each household is given in Table I. DA and balancing prices are adopted from Nordpool for 2019 [14].

Table I Household flexibility options

Household	DERs	Providing AS
1. Working couple	PV, BES, SA	Yes
2. Retired couple	SA	No
3. Students	BES, SA	Yes
4. Home-working family	PV, SA	No

We distinguish two subcases. In the first one described in *Section 2.1* the DSO directly controls BES charging and discharging and reduces the network charges for 10% on annual base for providing the service. Final users have a two-tariff pricing option, higher rate is set at 1.30 DKK/kWh during the day, and 0.95 DKK/kWh during night hours. The selling price is set to 1.035 DKK/kWh as 90% of the average buying price (average flat tariff and network charges 1.87 DKK/kWh are taken from [15]). It is assumed for both cases that flexibility is required after the closure of DA market, and that both the supplier and the aggregator face balancing costs if the flexibility is required. Due to limited space, only 4 final consumers are considered for the case study with different flexibility options, and in both cases it is assumed that the DSO requires flexibility from households 1 and 3 every day in hour 22. In the second subcase described in the *Section 2.2*, the aggregator sets the predefined values of lower and upper band of electricity price together with the daily average value (the same price bands are considered as in the first subcase). The DSO sends the request for flexibility to the aggregator who sets the RT electricity prices for final users considering both DA electricity price and request from the DSO. Figure 2 shows the difference between price signal sent to the user 1 (red line represents the case if the service is not activated and green line if the service is required). One can notice that the aggregator sets lower electricity prices for the final user who provides the service. Moreover, the price signal combines electricity component and the request from the DSO which is reflected as a price peak in hour 22 stimulating battery discharging and resulting in reduced power withdrawn from the grid.

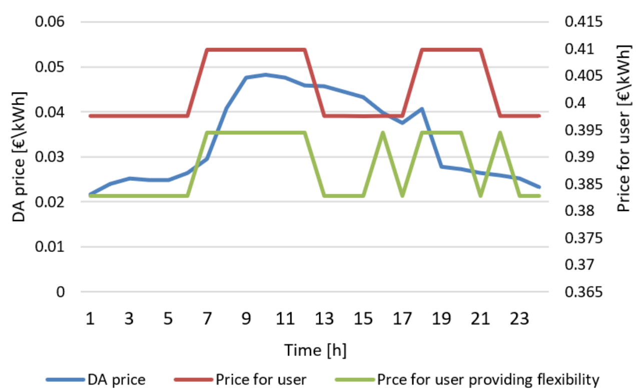

Figure 2 Prices for end user 1 for day 7

Profit of supplier and aggregator in both subcases before and after service provision is shown in Table II. Profit from final users and total profit before service provision shows the hypothetical cost in the case the service was not required. One can notice from Table II that the pricing mechanism provided by the aggregator is more beneficial then DSA in which direct load control is used. In DSA, the supplier does not gain any profit when the users provide flexibility service because the remuneration is paid directly to the final users (small changes in profit occur due to the load shifting in the hours with higher tariff).

Figure 3 presents the individual cost of each household divided in electricity component and network fee. Households 1 and 3 face higher total cost under CVA pricing mechanism compared with DSA with network charges reduction. Even the energy-based cost for customer 1 is equal in both cases, due to high network charges, it is more beneficial to get the annual discount from the DSO. Moreover, Customer 4 gains a higher profit in CVA case, however, due to high network charges for imported energy during lower price period makes it less profitable.

Future research will focus on the proposal of adequate pricing reduction for users under aggregator to achieve lower electricity cost compared to the DSA case.

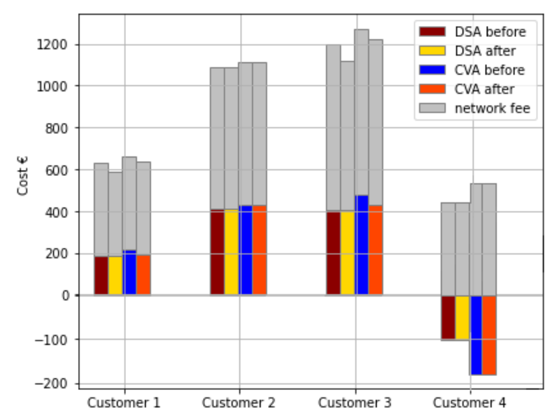

Figure 3 Individual cost under different pricing options

Table II Cost of supplier and aggregator in proposed approaches

Case	DSA		CVA	
	Before service provision	After service provision	Before service provision	After service provision
DA energy supply cost €	156.64	156.64	112.89	112.89
Balancing cost €	-	5.01	-	-16.54
Profit from service provision €	-	-	-	71.93
Profit from final users €	898.42	902.74	942.86	870.01
Total profit €	741.78	741.09	829.97	845.59

4. CONCLUSION AND FUTURE WORK

The paper develops the relationship models between the DSO, aggregator/supplier, and final users with a goal of comparing the results of two different options in demand response program: price based, and incentive based. The novelty in this paper is a proposal of unique price signal for each household which consider electricity price and also stimulates flexible behavior when requested from the DSO. The results show that the annual network charge reduction is more beneficial for final users, however pricing mechanism including DSO-aggregator interaction and bilevel price calculation brings higher profit for the aggregator.

The future work will include the detailed description of the bilevel model and price determination for providing flexibility service together with realistic network case in size and network problems. Moreover, further analysis will focus on the minimum flexibility price calculation and reduction in energy-based pricing component in the aggregator's approach which ensures that all final users involved in the AS provision face lower electricity cost with aggregator compared to the approach with direct load control.

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REFERENCES

[1] "2030 climate & energy framework | Climate Action." https://ec.europa.eu/clima/policies/strategies/2030_en (accessed Sep. 11, 2021).

[2] European Union Agency for the Cooperation of Energy Regulators, "ACER Report on Distribution Tariff Methodologies in Europe," no. February, p. 88, 2021.

[3] S. Huang, Q. Wu, M. Shahidehpour, and Z. Liu, "Dynamic power tariff for congestion management in distribution networks," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 2148–2157, 2019, doi: 10.1109/TSG.2018.2790638.

[4] B. S. K. Patnam and N. M. Pindoriya, "DLMP Calculation and Congestion Minimization with EV Aggregator Loading in a Distribution Network Using Bilevel Program," *IEEE Syst. J.*, vol. 15, no. 2, pp. 1835–1846, 2021, doi: 10.1109/JSYST.2020.2997189.

[5] S. Huang, Q. Wu, L. Cheng, Z. Liu, and H. Zhao, "Uncertainty Management of Dynamic Tariff Method for Congestion Management in Distribution Networks," *IEEE Trans. Power Syst.*, vol. 31, no. 6, pp. 4340–4347, 2016, doi: 10.1109/TPWRS.2016.2517645.

[6] V. Rigoni, D. Flynn, and A. Keane, "Coordinating Demand Response Aggregation with LV Network Operational Constraints," *IEEE Trans. Power Syst.*, vol. 36, no. 2, pp. 979–990, 2021, doi: 10.1109/TPWRS.2020.3014144.

[7] C. Zhang, J. Wu, Y. Zhou, M. Cheng, and C. Long, "Peer-to-Peer energy trading in a Microgrid," *Appl. Energy*, vol. 220, pp. 1–12, 2018, doi: https://doi.org/10.1016/j.apenergy.2018.03.010.

[8] "Zakon o obnovljivim izvorima energije i visokoučinkovitoj kogeneraciji," 2018. [Online]. Available: https://www.zakon.hr/z/827/Zakon-o-obnovljivim-izvorima-energije-i-visokoučinkovitoj-kogeneraciji.

[9] D. Li, W.-Y. Chiu, and H. Sun, "Demand Side Management in Microgrid Control Systems," in *Microgrid*, M. S. Mahmoud, Ed. Elsevier, 2017, pp. 203–230.

[10] S. I. Gass and M. C. Fu, Eds., "Karush-Kuhn-Tucker (KKT) Conditions," in *Encyclopedia of Operations Research and Management Science*, Boston, MA: Springer US, 2013, pp. 833–834.

[11] J. Fortuny-Amat and B. McCarl, "A Representation and Economic Interpretation of a Two-Level Programming Problem," *J. Oper. Res. Soc.*, vol. 32, no. 9, pp. 783–792, 1981, doi: 10.1057/jors.1981.156.

[12] "Load Profile Generator." https://www.loadprofilegenerator.de/ (accessed Oct. 19, 2021).

[13] "Renewables ninja." https://www.renewables.ninja/ (accessed Oct. 20, 2021).

[14] "Nord Pool prices." https://www.nordpoolgroup.com/ (accessed Oct. 19, 2021).

[15] "SEAS-NVE electricity prices." https://seas-nve.dk/el/ (accessed Oct. 10, 2021).

