Integration of DERs in the Aggregator Platform for the Optimal Participation in Wholesale and Local Electricity Markets

Author(s): Haghifam, Sara; Laaksonen, Hannu; Shafie-khah, Miadreza

Title: Integration of DERs in the Aggregator Platform for the Optimal Participation in Wholesale and Local Electricity Markets

Year: 2021

Versio: Published version

Please cite the original version:

Haghifam, S., Laaksonen, H. & Shafie-khah, M. (2021). Integration of DERs in the Aggregator Platform for the Optimal Participation in Wholesale and Local Electricity Markets. *CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution*, 2129-2133. https://doi.org/10.1049/icp.2021.1657

Integration of DERs in the Aggregator Platform for the Optimal Participation in Wholesale and Local Electricity Markets

Sara Haghifam [1]***, Hannu Laaksonen*** [1*]***, Miadreza Shafie-khah*** [1]
[1] *Flexible Energy Resources, School of Technology and Innovations, University of Vaasa, 65200 Vaasa, Finland*
* *hannu.laaksonen@uwasa.fi*

Keywords: DER aggregator; Offering strategy; Local electricity market; Price-maker; Bi-level programming.

Abstract

This paper aims to present a novel optimization model for the offering strategy of a distributed energy resource aggregator (DER AG) as a price-maker entity in the local electricity market (LEM). Accordingly, the DER AG integrates various non-dispatchable and dispatchable generation units as well as energy storage systems to submit its offers to the operator of the LEM. The operator settles the LEM based on received offers from the DER AG and its rivals in the electricity distribution network. On the other hand, since this agent aggregates a considerable number of DERs' capacity at the local level, the simultaneous participation of the DER AG as a price-taker player in the wholesale electricity market (WEM) is provided as well. To address the raised decision-making problem, a bi-level programming method is employed in this work. In this regard, the upper-level (UL) of the problem attempts to maximize the DER AG's expected profit from taking part in both LEM and WEM, while the lower-level (LL) seeks to clear the LEM through maximizing the social welfare. Ultimately, a typical case study is implemented to investigate the impact of simultaneous involvement in both markets on DER AG's optimal performance.

Nomenclature

Acronyms	
AG	Aggregator
BESU	Battery Energy Storage Unit
DA	Day-Ahead
DER	Distributed Energy Resource
DSO	Distribution System Operator
LEM	Local Electricity Market
LL	Lower-Level
PV	Photovoltaic System
UL	Upper-Level
WEM	Wholesale Electricity Market
WT	Wind Turbine
Indices and Sets	
$b \in B$	BESUs of the DER AG
$d \in D$	Demands of the LEM
$i \in I$	Dispatchable sources of the DER AG
$r \in R$	Rivals of the DER AG in the LEM
$t \in T$	Time periods
$v \in V$	PVs of the DER AG
$w \in W$	WTs of the DER AG
Ξ^{LL}	Set of the LL's decision variables
Ξ^{UL}	Set of the UL's decision variables
Parameters	
$P_{de}^{max}(d,t), P_{de}^{min}(d,t)$	Maximum/minimum amount of the dth demand in the LEM during time t (MW)
$P_{riv}^{max}(r,t), P_{riv}^{min}(r,t)$	Maximum/minimum generation capacity of the rth rival in the LEM during time t (MW)
$P_{vAG}^{F}(v,t)$	Power forecast of the vth PV during time t (MW)
$P_{wAG}^{F}(w,t)$	Power forecast of the wth WT during time t (MW)
$\lambda_{de}(d,t)$	Bid price of the dth demand in the LEM during time t ($/MWh)
$\lambda_{iAG}(i)$	Marginal price of the ith dispatchable source ($/MWh)
$\lambda_{riv}(r,t)$	Offer price of the rth rival in the LEM during time t ($/MWh)
$\lambda^{WEM,DA}(t)$	Price forecast of the DA WEM during time t ($/MWh)
Variables	
$P_{chAG}(b,t)$	Charge power of the bth BESU during time t (MW)
$P_{dchAG}(b,t)$	Discharge power of the bth BESU during time t (MW)
$P_{de}(d,t)$	Consumed power by the dth demand in the LEM during time t (MW)
$P_{iAG}(i,t)$	Generated power by the ith dispatchable source during time t (MW)
$P_{riv}(r,t)$	Produced power by the rth rival in the LEM during time t (MW)
$q_{AG}^{LEM,DA}(t)$	Accepted offer of the DER AG in the DA LEM during time t (MW)
$q_{AG}^{LEM,DA,Of}(t)$	Quantity offer of the DER AG to the DA LEM during time t (MW)
$q_{AG}^{WEM,DA}(t)$	Offer of the DER AG to the DA WEM during time t (MW)
$\lambda^{LEM,DA}(t)$	Market-clearing price of the DA LEM during time t ($/MWh)
α, β, μ	Dual variables for constraints of the LL problem

1 Introduction

During the last few years, the number of small-scale and medium-scale DERs has increased drastically in electricity distribution networks. The presence of various DERs at the local distribution level has changed traditional power systems with centralized structures to re-structured power systems with decentralized models [1]. While the existence of these resources improves re-structured distribution systems' flexibility, reliability, efficiency, and voltage profile, the optimal operation of these networks with the significant penetration of DERs is confronted with several challenges. For one thing, a great number of DERs have to be managed by the distribution system operator (DSO), but an appropriate local or DSO-level market scheme for the considered goal does not exist today. To deal with this problem, normally, take-or-pay contracts are made between system operators and DER owners at fixed prices that are lower than market prices [2]. Nonetheless, since owners of distributed units are not able to gain the maximum possible amount of profit by signing these kinds of contracts, their tendency to participate in the DSO's energy management program is reduced. As a result, system operators do not benefit from the widespread deployment of DERs and their offered privileges. Hence, providing an opportunity in which a wide range of DERs are managed at the distribution level to have local energy trading with one another and with system operators is highly required. This objective could be achieved by designing a potential LEM.

In general, the generation capacity of DERs varies from a few kilowatts to a small number of megawatts. Since these units do not have a sizable capacity to meet the market threshold, they are not able to take part in system-wide or TSO-level market schemes individually [3]. On the other hand, the stochastic nature of a considerable percentage of DERs prevents these sources from effective participation in the potential LEM or the DSO's energy management program. To handle these challenges, currently, a concept called the AG platform for aggregating the capacity of DERs has been raised [4]. In this regard, multiple decentralized real and virtual generation units collaborate in the form of a coalition to not only trade the energy with each other but also compensate for/supply their shortage/surplus by taking part in varied electricity markets, namely the WEM as well as potential LEM. By defining such a cooperative environment among several DERs, owners of these small-scale units have the capability to exercise the market power and promote their income significantly.

Recently, various research studies have been carried out on the market design for local energy exchange as well as the involvement of AGs in different electricity markets. For instance, a leader-follower game-based framework has been exploited in [5] to model a LEM for the transactive energy exchange at the distribution level. In this case, the DSO, as the LEM operator, interacts with a DER AG, as an independent financial agent who has integrated several generation and storage units. Besides the LEM, these two autonomous players are able to take part in the WEM as price-taker entities as well. To implement the energy management problem of various microgrids in the LEM platform, a two-level decision-making scheme has been provided in [6]. In the first level of this model, multiple microgrids attempt to minimize their operating costs by sending their bids/offers to the operator of the LEM, while in the second level, the LEM clearing procedure is performed. For the bidding strategy of an AG in both WEM and LEM, a robust methodology has been suggested in [7]. This programming is implemented from the AG's standpoint in order to reduce operating costs and provide the DSO's flexibility requirements at the local platform. To improve the optimal performance of re-structured distribution systems, a Day-Ahead (DA) LEM has been proposed in [8], in which different consumers, producers as well as prosumers at the local level are able to be managed by taking part in this market. The potential DA LEM is settled by the system operator to not only maximize the entire players' social welfare but also satisfy the distribution system's technical constraints. For the involvement of DERs in a potential LEM, two different strategies have been addressed in [9]. In the first one, DERs are dispatched and administered centrally by the LEM operator, while in the second one, these distributed sources are managed by an AG to take part in the market independently. Ultimately, the optimal participation of a DER AG, as a price-taker organization, within the WEM has been investigated in [10]. The studied AG manages different real and virtual resources located in the distribution system to promote its expected profit in the bidding process.

Reviewing the existing works demonstrates that, generally, the potential LEMs have been modeled from the system or market operators' perspectives. Hence, distribution networks' available prosumers, producers, and consumers have been considered as price-taker participants in these markets. However, players with a significant share of power in the market will have the chance to exercise market power and alter the market prices for their own benefits. Therefore, developing models in which the scheduling is conducted from a strategic player's viewpoint as a price-maker agent in the potential LEM is necessary. Moreover, owing to several technical as well as business challenges, owners of DERs do not have the capability to simultaneously participate in both potential LEM and WEM. Accordingly, most of the previous studies have failed to provide pragmatic solutions to deal with these challenges and reach the considered purpose. Consequently, since this work is intended to deal with the mentioned research gaps, two of the key contributions of the paper can be highlighted as follows:

1. Defining an AG of decentralized DERs to integrate the capacity of local resources and create a proper cooperative environment among them for effective energy trading in both potential LEM and WEM.

2. Providing a novel optimization model for the offering strategy of the studied DER AG as a strategic player in a potential LEM and in the presence of multiple rivals like microgrids and demand response aggregators.

2 Methodology

As mentioned earlier, the primary goal of the study is to present a practical framework for the optimal participation of a wide range of small and medium-sized DERs in both potential LEM and WEM. To this end, an AG platform is proposed in which the capacity of distributed units are aggregated to not only be eligible for involvement in the wholesale market trading as a price-taker player but also gain local market power and change market-clearing outcomes as a strategic player. For modeling the offering strategy of the considered DER AG in both markets, a bi-level programming approach [11] is exploited in this paper. The outline of the suggested bi-level model is displayed in Figure 1.

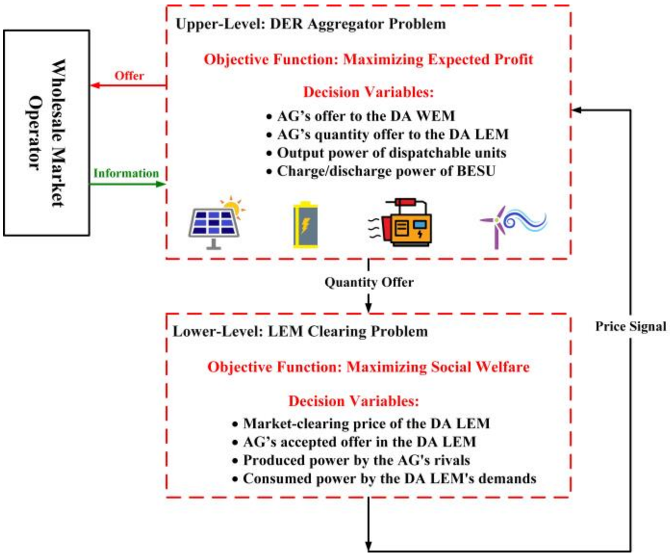

Figure 1. Bi-level decision-making framework.

As shown in Figure 1, at the UL of the problem, the DER AG maximizes its expected profit from taking part in both potential LEM and WEM and derives the quantity of its offers to the DA market operators. In contrast, according to submitted offers of the DER AG and its rivals in the distribution network, the system operator clears the LEM at the LL to maximize the social welfare of the market and derive market-clearing prices. By maximizing the social welfare, each consumer's surplus and each producer's surplus is increased, which leads to the improvement of the potential LEM's efficiency. For better clarification of the raised bi-level framework, non-linking and linking decision variables of the UL and LL are stated in Figure 1 as well.
In the following, objective functions and technical constraints of both levels are mathematically formulated.

2.1 Problem Formulation of the UL

The objective function of the UL is to maximize the DER AG's daily profit that could be defined as the difference between its revenue from taking part in both DA WEM and DA LEM and its operating costs.

$$\begin{aligned}\mathrm{OF}_{\mathrm{UL}} = \mathrm{Max} \sum_{t=1}^{T} \Big\{ & q_{\mathrm{AG}}^{\mathrm{WEM,DA}}(t)\cdot\lambda^{\mathrm{WEM,DA}}(t) \\ & + q_{\mathrm{AG}}^{\mathrm{LEM,DA}}(t)\cdot\lambda^{\mathrm{LEM,DA}}(t) - \sum_{i=1}^{I} P_{\mathrm{iAG}}(i,t)\cdot\lambda_{\mathrm{iAG}}(i) \Big\}\end{aligned} \tag{1}$$

Subject-to:
1- Energy balance constraint of the DER AG:
Clearly, the AG's offers to the DA LEM and DA WEM should be matched with its production and storage capacities. Accordingly, the DA energy balance of the entity during time t can be stated by Eq. (2).

$$\begin{aligned} & q_{\mathrm{AG}}^{\mathrm{WEM,DA}}(t) + q_{\mathrm{AG}}^{\mathrm{LEM,DA}}(t) = \sum_{w=1}^{W} P_{\mathrm{wAG}}^{F}(w,t) + \sum_{v=1}^{V} P_{\mathrm{vAG}}^{F}(v,t) \\ & + \sum_{i=1}^{I} P_{\mathrm{iAG}}(i,t) + \sum_{b=1}^{B}\big(P_{\mathrm{dchAG}}(b,t) - P_{\mathrm{chAG}}(b,t)\big), \quad \forall t \end{aligned} \tag{2}$$

2- Offers to the DA WEM and DA LEM constraints:
Quantity offers of the DER AG to both markets are non-negative variables, as shown by inequalities (3) and (4).

$$q_{\mathrm{AG}}^{\mathrm{WEM,DA}}(t) \geq 0, \quad \forall t \tag{3}$$

$$q_{\mathrm{AG}}^{\mathrm{LEM,DA,Of}}(t) \geq 0, \quad \forall t \tag{4}$$

3- Dispatchable and storage units' constraints:
Dispatchable generation units' operational constraints and their power limitations are taken into account, as stated in [12]. Additionally, Battery Energy Storage Units' (BESUs) charge/discharge power limitations as well as their stored energy limitations are considered, as expressed in [13].
In the end, the UL's set of decision variables are listed as follows:

$$\Xi^{\mathrm{UL}} = \left\{ q_{\mathrm{AG}}^{\mathrm{WEM,DA}}(t), q_{\mathrm{AG}}^{\mathrm{LEM,DA,Of}}(t), P_{\mathrm{iAG}}(i,t), P_{\mathrm{dchAG}}(b,t), P_{\mathrm{chAG}}(b,t) \right\}$$

2.2 Problem Formulation of the LL

The LL problem represents the DA LEM clearing process with the aim of maximizing the market social welfare. This objective function is modeled as the difference between the utility of all buyers and the cost of all sellers.

$$\begin{aligned}\mathrm{OF}_{\mathrm{LL}} = \mathrm{Max} \sum_{t=1}^{T} \Bigg\{ & \sum_{d=1}^{D} P_{\mathrm{de}}(d,t)\cdot\lambda_{\mathrm{de}}(d,t) \\ & - \sum_{r=1}^{R} P_{\mathrm{riv}}(r,t)\cdot\lambda_{\mathrm{riv}}(r,t) \Bigg\}\end{aligned} \tag{5}$$

Subject-to:
1- Energy balance constraint of the DA LEM:
Accepted offers of producers must satisfy the demands of the market during time t.

$$q_{\mathrm{AG}}^{\mathrm{LEM,DA}}(t) + \sum_{r=1}^{R} P_{\mathrm{riv}}(r,t) = \sum_{d=1}^{D} P_{\mathrm{de}}(d,t); \quad \lambda^{\mathrm{LEM,DA}}(t), \quad \forall t \tag{6}$$

2- Offer and bid constraints in the DA LEM:
In the LEM clearing process, the accepted offer of the strategic DER AG, which is a non-negative variable, should be restricted to its quantity offer to the DA LEM, as shown in inequality (7).

$$0 \leq q_{\mathrm{AG}}^{\mathrm{LEM,DA}}(t) \leq q_{\mathrm{AG}}^{\mathrm{LEM,DA,Of}}(t); \quad \underline{\mu}(t), \overline{\mu}(t), \quad \forall t \tag{7}$$

$$P_{\mathrm{riv}}^{\min}(r,t) \leq P_{\mathrm{riv}}(r,t) \leq P_{\mathrm{riv}}^{\max}(r,t); \quad \underline{\alpha}(r,t), \overline{\alpha}(r,t), \quad \forall r,t \tag{8}$$

$$P_{\mathrm{de}}^{\min}(d,t) \leq P_{\mathrm{de}}(d,t) \leq P_{\mathrm{de}}^{\max}(d,t); \quad \underline{\beta}(d,t), \overline{\beta}(d,t), \quad \forall d,t \tag{9}$$

It is notable that dual variables of the LL's constraints are represented following a semicolon.
Ultimately, the LL's set of decision variables are listed as follows:

$$\Xi^{\mathrm{LL}} = \left\{ \begin{array}{l} q_{\mathrm{AG}}^{\mathrm{LEM,DA}}(t), P_{\mathrm{de}}(d,t), P_{\mathrm{riv}}(r,t), \lambda^{\mathrm{LEM,DA}}(t) \\ \underline{\mu}(t), \overline{\mu}(t), \underline{\alpha}(r,t), \overline{\alpha}(r,t), \underline{\beta}(d,t), \overline{\beta}(d,t) \end{array} \right\}$$

Since the LL problem is linear, continuous, and hence convex, the raised bi-level model can be reformulated to a single-level model by replacing the LL with its Karush-Kuhn-Tucker (KKT) conditions [14]. However, the final single-level model of the problem is non-linear due to the presence of some sources of non-linearities. For the linearization of these sources, the Strong Duality Theorem (SDT) and the Big-M method are utilized in this research work [15].

3 Results

To assess the effectiveness of the presented methodology for the simultaneous involvement of one DER AG in both potential LEM and WEM, a typical case study is implemented in this part of the article. The studied DER AG consists of sundry non-dispatchable and dispatchable generation units as well as BESUs. Technical specifications of these resources are summarized in Table 1.

Table 1. Input data of available DERs inside the AG.

Dispatchable Sources			
Max Power (MW)	Min Power (MW)	Marginal Price ($/MWh)	Ramp-up/down (MW/h)
2 × 2	2 × 0.2	41	0.5
2 × 2.5	2 × 0.25	51	0.5
Wind Turbines			
Rated Power (MW)	Rated Speed (m/s)	Cut-in Speed (m/s)	Cut-out Speed (m/s)
2 × 2	13	4	25
4 × 1.25	11	3	25
5 × 1	12.5	3.6	20
Photovoltaic Systems			
Rated Power (MW)		Reference Temperature (°C)	
2 × 3		25	
4 × 1		25	
Battery Energy Storage Units			
Min / Max Storage Capacity (MWh)		Charge / Discharge Power Capacity (MW)	
2 / 10		2.5 / 2.5	

As for the DA LEM, it is assumed that six power producers send their offers to the market operator as the DER AG's rivals. On the contrary, four consumers send their bids to the DA LEM as the demand of the market.

The considered DER AG's offers to the potential LEM and WEM, as well as the LEM clearing price and WEM forecasted price, are illustrated in Figure 2. As it is clear in Figure 2, the DER AG tends to sell more power to the WEM when the WEM price is more than the LEM price and vice versa. Furthermore, when market prices are too close to each other, such as hour 19, the AG supplies its production to both markets.

The share of each type of DER in the AG's total traded power with both markets is shown in Figure 3. Clearly, the DER AG has exploited its BESU to transfer some part of its production from off-peak hours to peak hours. This matter leads to an increase in the daily profit of the DER AG. Moreover, based on Figure 3, the AG has utilized its dispatchable units only in hours 8 to 24 for more effective participation in both markets. Nonetheless, during hours 1 to 7, dispatchable units are kept off because their marginal prices are higher than both market prices.

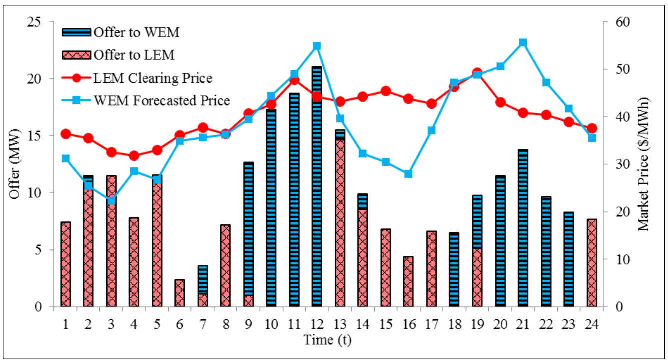

Figure 2. AG's offers to both markets and DA market prices.

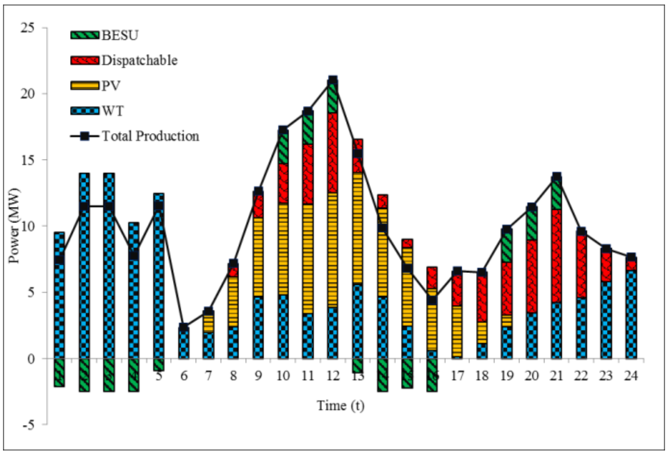

Figure 3. Optimal dispatch of local units inside the AG.

In order to better investigate the total revenue of the DER AG during the studied day, the revenue distribution of this entity is depicted in Figure 4.

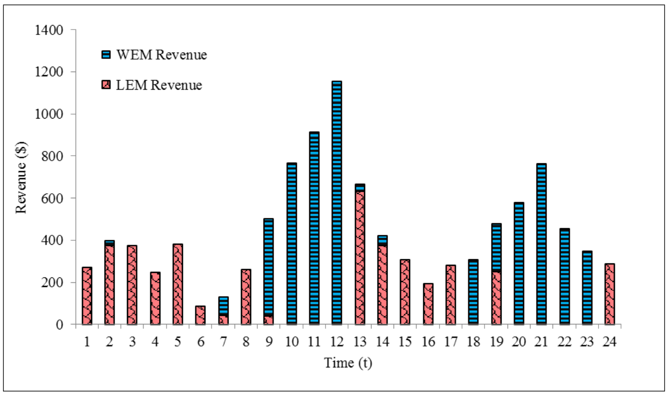

Figure 4. DER AG's revenue distribution during the day.

Accordingly, at hours 11 and 12, the DER AG has obtained the highest amount of income from taking part in the DA

WEM, where the AG's power production and the WEM price are at the highest value. In Table 2, the DER AG's optimal performance in the presence of both markets is compared with situations in which this player is only able to participate in one electricity market. Based on this table, the AG has gained the highest amount of profit by participating in both electricity markets. In addition, by taking part in only WEM and only LEM, the AG has lost nearly about 9.5% and 10.5% of its daily benefit respectively.

Table 2. DER AG's optimal operation in three different cases.

	Only WEM	Only LEM	Both LEM and WEM
Traded Energy (MWh/day)	236.1	204.9	242.7
Revenue ($/day)	9567.3	8127.3	10559.2
Cost ($/day)	2007.0	630.4	2276.0
Profit ($/day)	7560.3	7496.9	8283.2

4 Conclusion

A pragmatic framework was provided in this paper for the simultaneous participation of multiple small and medium-scale DERs located at the distribution level in the potential LEM and WEM. To this end, an AG platform was suggested in which different DERs like dispatchable units, WTs, PVs, and BESUs cooperate with one another to not only trade the energy in the WEM as a price-taker player but also exercise the LEM power and change the market-clearing results to their own benefit as a strategic participant. For solving the raised problem, a bi-level programming approach was executed in this paper. At the UL of this problem, the DER AG attempts to promote its daily profit from taking part in both DA LEM and DA WEM, whereas at the LL, the LEM clearing process is implemented. To scrutinize the effectiveness of the suggested model, the optimal operation of the DER AG in the case that participates in both markets was compared with the cases in which it participates in only one market.

5 Acknowledgements

This work was undertaken as part of the FLEXIMAR project (novel marketplace for energy flexibility) with financial support provided by Business Finland (Grant No. 6988/31/2018) as well as Finnish companies.

6 References

[1] Khorasany, M., Mishra, Y., and Ledwich, G., 'Market Framework for Local Energy Trading: A Review of Potential Designs and Market Clearing Approaches', IET Generation, Transmission & Distribution, 2018, 12, (22), pp. 5899-5908.

[2] Feng, C., Li, Z., Shahidehpour, M., Wen, F., and Li, Q., 'Stackelberg Game Based Transactive Pricing for Optimal Demand Response in Power Distribution Systems', International Journal of Electrical Power & Energy Systems, 2020, 118, p. 105764.

[3] Lu, X., Li, K., Xu, H., Wang, F., Zhou, Z., and Zhang, Y., 'Fundamentals and Business Model for Resource Aggregator of Demand Response in Electricity Markets', Energy, 2020, p. 117885.

[4] Ikäheimo, J., Evens, C., and Kärkkäinen, S., 'Der Aggregator Business: The Finnish Case', Technical Research Centre of Finland (VTT): Espoo, Finland, 2010.

[5] Haghifam, S., Zare, K., Abapour, M., Muñoz-Delgado, G., and Contreras, J., 'A Stackelberg Game-Based Approach for Transactive Energy Management in Smart Distribution Networks', Energies, 2020, 13, (14), p. 3621.

[6] Sheikhahmadi, P., Bahramara, S., Shahrokhi, S., Chicco, G., Mazza, A., and Catalão, J.P., 'Modeling Local Energy Market for Energy Management of Multi-Microgrids', in, 2020 55th International Universities Power Engineering Conference (UPEC), (IEEE, 2020)

[7] Correa-Florez, C.A., Michiorri, A., and Kariniotakis, G., 'Optimal Participation of Residential Aggregators in Energy and Local Flexibility Markets', IEEE Transactions on Smart Grid, 2019, 11, (2), pp. 1644-1656.

[8] Bahramara, S., Sheikhahmadi, P., Lotfi, M., Catalão, J.P., Santos, S.F., and Shafie-khah, M., 'Optimal Operation of Distribution Networks through Clearing Local Day-Ahead Energy Market', in, 2019 IEEE Milan PowerTech, (IEEE, 2019)

[9] Hatziargyriou, N.D. and Asimakopoulou, G.E., 'Der Integration through a Monopoly Der Aggregator', Energy Policy, 2020, 137, p. 111124.

[10] Wang, F., Ge, X., Yang, P., Li, K., Mi, Z., Siano, P., and Duić, N., 'Day-Ahead Optimal Bidding and Scheduling Strategies for Der Aggregator Considering Responsive Uncertainty under Real-Time Pricing', Energy, 2020, 213, p. 118765.

[11] Sinha, A., Malo, P., and Deb, K., 'A Review on Bilevel Optimization: From Classical to Evolutionary Approaches and Applications', IEEE Transactions on Evolutionary Computation, 2017, 22, (2), pp. 276-295.

[12] Haghifam, S., Najafi-Ghalelou, A., Zare, K., Shafie-khah, M., and Arefi, A., 'Stochastic Bi-Level Coordination of Active Distribution Network and Renewable-Based Microgrid Considering Eco-Friendly Compressed Air Energy Storage System and Intelligent Parking Lot', Journal of Cleaner Production, 2020, 278, p. 122808.

[13] Haghifam, S., Dadashi, M., Zare, K., and Seyedi, H., 'Optimal Operation of Smart Distribution Networks in the Presence of Demand Response Aggregators and Microgrid Owners: A Multi Follower Bi-Level Approach', Sustainable cities and society, 2020, 55, p. 102033.

[14] Dadashi, M., Haghifam, S., Zare, K., Haghifam, M.-R., and Abapour, M., 'Short-Term Scheduling of Electricity Retailers in the Presence of Demand Response Aggregators: A Two-Stage Stochastic Bi-Level Programming Approach', Energy, 2020, p. 117926.

[15] Ruiz, C. and Conejo, A.J., 'Pool Strategy of a Producer with Endogenous Formation of Locational Marginal Prices', IEEE Transactions on Power Systems, 2009, 24, (4), pp. 1855-1866.