A New Local Market Structure for Meeting Customer-Level Flexibility Needs

Author(s): Khajeh, Hosna; Firoozi, Hooman; Laaksonen, Hannu; Shafie-khah, Miadreza

Title: A New Local Market Structure for Meeting Customer-Level Flexibility Needs

Year: 2020

Version: Submitted version

Please cite the original version:

Khajeh, H., Firoozi, H., Laaksonen, H. & Shafie-khah, M. (2020). A New Local Market Structure for Meeting Customer-Level Flexibility Needs. *2020 International Conference on Smart Energy Systems and Technologies (SEST)*, 1-6. https://doi.org/10.1109/SEST48500.2020.9203499

A New Local Market Structure for Meeting Customer-Level Flexibility Needs

Hosna Khajeh
School of Technology and Innovations
University of Vaasa
Vaasa, Finland
hosna.khajeh@uwasa.fi

Hooman Firoozi
School of Technology and Innovations
University of Vaasa
Vaasa, Finland
hooman.firoozi@uwasa.fi

Hannu Laaksonen
School of Technology and Innovations
University of Vaasa
Vaasa, Finland
hannu.laaksonen@uwasa.fi

Miadreza Shafie-khah
School of Technology and Innovations
University of Vaasa
Vaasa, Finland
miadreza.shafiekhah@uwasa.fi

***Abstract*— This paper proposes a new local market structure for meeting customer-level flexibility need. In the proposed market structure, the flexibility need of each customer is divided into two parts regarding to the uncertainty coming from forecast errors and variability of the renewable energy sources. In addition, the flexible energy resources are categorized into three types according to the controllability of the flexible resource. Finally, the local flexibility market is settled by matching the flexibility provision with the flexibility needs. This is done by considering simultaneously the needed flexibility types with the type of available flexibilities. The local flexibility market is implemented for a hypothetical test system in order to prove the efficiency of the proposed market structure.**

Keywords—flexibility, flexible resources, local market, local flexibility market

I. INTRODUCTION

Uncertainties resulting from the intermittent characteristic of renewable energy resources as well as their unpredictable behavior pose a major challenge for the reliability and stability of the future power system. In addition to the transmission level, the challenges are increasing also at the distribution level. Flexible energy resources can be considered as a very potential solution to maintain the balance between generation and consumption in the future renewables based system [1]. These flexible resources can be located in either generation- or demand-side of the power system. Generation-side resources have been conventionally utilized to provide the system with flexibility services [2]. However, small-scale demand-side flexible resources (like batteries, electric vehicles, controllable appliances, and renewable generation e.g. solar panels) have recently attracted increasing interest.

Small-scale demand-side flexible resources mostly consist of customers and prosumers who can modify their consumption and/or have controllable generation resources. Although system operators (transmission and distribution system operators, TSOs and DSOs) may be considered as main flexibility buyers, also customers and prosumers should be capable of buying flexibility for avoiding the possible penalty due to the sudden variation in their renewable resources.

Small-scale customers with different types of flexible resources such as storages, controllable and flexible appliances (loads) and electric vehicles (EVs) can be considered as customer-level flexibility providers on demand-side of the power system. The customer load can consist of non-flexible as well as flexible (controllable/shiftable) loads [3]. In addition, energy storage related resources like batteries and EVs can be utilized as another source of flexibility.

Household controllable appliances/devices (loads) can be categorized into three types: 1) interruptible appliances like EVs, 2) non-interruptible appliances such as washing machine and 3) thermostatically controlled appliances such as air conditioning devices [4]. Taking into account the user’s preference, the home energy management system (HEMS) decides the optimal operation time and power for the devices depending on the type of device.

Different customer-level flexibility trading schemes has been presented previously in the literature. For example, in [5] authors introduced a local market structure in which users of the bottom-layer of the system can participate in the local market with respect to flexibility. Ref. [6] defined a local-market-based approach from EMPOWER-project in which different services, including flexibility, could be provided through negotiating contracts among the market players. In [7], a decision-support system was proposed in which local market participants can offer their flexibility capacities through MASCEM-platform [8]. In [9], a decentralized local load management was designed so as to trade demand-side flexibility between prosumers and aggregators. In [10], the peak shaving services during peak hours was proposed as a flexibility service, meaning that the DSO can purchase the flexibility service from demand-side aggregators according to the monthly contracts. In [11] customers were proposed to present their available flexibility in terms of their controllability (curtailable or shiftable) to the aggregator aiming to make profits.

However, to the best of authors’ knowledge, there exists no research related to a local market for meeting customer-level flexibility needs. Small-scale prosumers and customers need to be able to trade flexibility with each other as a commodity in order to meet their flexibility need in real-time. They may need flexibility in order to compensate the uncertainty and variability of their intermittent resources and to avoid the penalty costs or their profit reduction. In this way, this paper proposes a flexibility local market with the aim of supplying local flexibility needs and demand. Local flexibility sellers are considered to have different kinds of flexible resources ranging from household appliances to batteries. Local flexibility buyers are supposed to have renewable resources. The flexibility need (demand) is also divided into two parts according to the type of flexibility need. At the end, the local flexibility market is cleared by considering simultaneously the needed flexibility types with the type of available flexibilities.

The proposed local market brings the following benefits to the power system:

- ✓ Fulfills the local customer flexibility needs,
- ✓ Fulfills partially the DSO flexibility needs, and
- ✓ Helps system operators (TSO and DSOs) because the local customer-level flexibility needs can be provided by local customer-level resources.

The rest of the paper is organized as follows. Section II introduces the structure of the proposed local flexibility market. Section III defines problem formulation for the clearing process of the proposed market. Section IV introduces the case study and implements the proposed local market for the test system. Finally, section V concludes the paper.

II. Proposed Local Flexibility Market

Local flexibility market (LFM) is proposed with the aim to satisfy the customer-level flexibility needs. The flexibility market should be formed in real-time, near to the actual trading time so that there would not exist any uncertainties and variabilities due to intermittent renewable generation.

Local flexibility market operator (LFMO) is an entity who is responsible for clearing flexibility bids and offers of the players in order to compensate the variability and uncertainty associated with renewable resources. It is assumed that prosumers with variable resources (such as rooftop PV panels) has offered their forecasted available capacities in day-ahead or intraday local markets. However, in real-time there may be a deviation between the actual production and the scheduled amount, imposing penalty costs for the owners of the resource. The reasons behind this deviation can be as follows:

- Uncertainty due to the error of renewable-generation forecast and
- Variability due to the intermittent characteristic of renewable resources resulting from their dependency on the weather and other environmental factors like moving cloud patterns.

In this regard, the proposed LFM tries to compensate for the deviations between the real-time and the scheduled amount through matching the flexibility offers of the local players with the flexibility bids. As a result, the local flexibility needs are satisfied locally while benefiting the entire local players participating in the LFM. In fact, the flexibility sellers make profits and the flexibility buyers avoid financial penalty costs. Moreover, the LFM benefits the DSO as it can be a solution to the local flexibility issues in the distribution system.

A. Control layer

The proposed model is designed based on the hybrid control architecture which is a combination of hierarchical and decentralized control and management architectures for the future power system [12]. Fig. 1 illustrates the control structure of the proposed model. In this way, local players who are mainly households can fully control their flexible resources and build their bidding/offering strategies for flexibility trading while their bids/offers are managed and controlled by the LFMO.

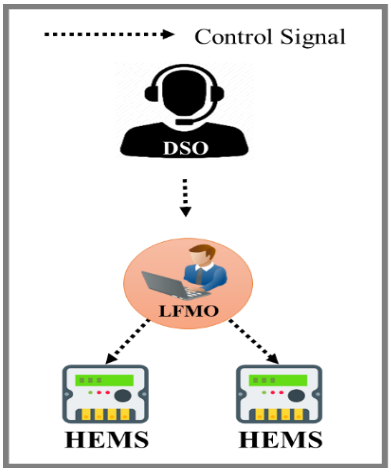

Fig. 1. Control structure of the proposed LFM

The combination of decentralized and hierarchical structures can provide the model with democracy-related benefits of liberalized models as well as the coordination and management benefits of supervised approaches. On the one hand, flexible resource owners located at the customer level are able to compete with each other to sell their flexibility capacities. Flexibility buyers are also competing to compensate for the variability and uncertainty of their own renewable resources. On the other hand, the local operator who also acts as a mediator between the system operator and the local sellers would manage the flexibility transactions of the local traders. Thus, at the lower level, households control their flexible resources through the use of a HEMS. At the higher level, the DSO sends control signal to the LFMO and the LFMO controls the flexible resources to satisfy flexibility needs of the local intermittent resources based on the bids and offers of the participants.

B. Communication layer

The existence of the secured information and communication infrastructure is of vital necessity when designing the LFM. The required information and communication system should integrate local flexibility sellers and buyers within a platform so that they are given the option to have equal access for buying/selling flexibility from/to the local market [13].

Bi-directional flow of information is required to connect the market players with the LFMO. The suitable platform gives the option to the LFMO to match the flexibility offers with flexibility bids aiming to fulfill the local flexibility requirements. The LFMO may impose restriction on the flexibility bids and offers through the platform to apply the voltage and congestion-related constraints in order to ensure network security and stability. Besides, the LFMO can send some signals to the participants and direct consumers and prosumers towards meeting the local flexibility needs.

C. Trading layer

In the trading layer, participants (sellers and buyers) trade flexibility in each time slot. The time slots for trading flexibility need to be small in a way that the flexible appliance can be scheduled more conveniently. For example, this paper considers a 15-min time slot for trading flexibility. Hence, the player submits its bids or offers an hour ahead for the next four 15-min time slots.

In the proposed LFM, the prices of flexibility trading are considered to be determined by the LFMO. The LFMO specifies the prices for each trading time slot and for each type of flexible resource.

The buyers of flexibility submit their required flexibility demand while the sellers offer their available capacities for the flexibility purpose. A buyer submits two types of flexibility demand for each upward or downward flexibility need. Likewise, the sellers submit three types of downward or upward flexibility capacities based on its available flexible resources. Finally, the LFMO matches the buying offers with the selling bids with the aim of fulfilling the local flexibility need.

1) Flexibility need/demand

Flexibility need/demand of each prosumer is divided into "flexibility demand for power variability" (FDPV) and "flexibility demand for forecast uncertainty" (FDFU). The flexibility capacities utilized for FDPV should compensate for the variability of renewable power originating from weather-related and environmental dependencies whereas the flexibility production deployed for FDFU should cover the forecast errors associated with renewable.

2) Flexible resources

Flexibility sellers participating in the LFM can have three types of flexible resources. Fig. 2 illustrates the different types of flexible resources owned by a seller and the types of demand for the buyer in the LFM.

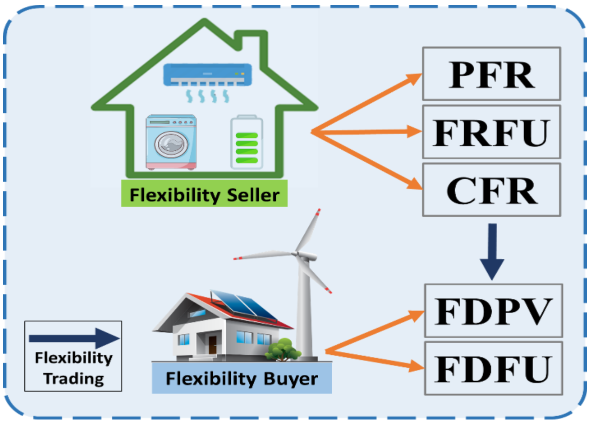

Fig. 2. Different types of flexibility demand and flexible resources in the proposed LFM

The first type of flexible resources, named preliminary flexible resources (PFR), are the appliances whose working power cannot be controlled or managed, but their working time can be shifted or curtailed in order to provide the required flexibility. These resources are also considered as time flexibility [14]. Washing machine and electric vehicles charged under a fixed power mode are regarded as two examples of PFRs.

The second type, named "flexible resources for forecast uncertainty" (FRFU) are those whose working power as well as their working time can be controlled, but they are not flexible enough to be utilized for FDPV need. In other words, the only flexibility demand that they can meet is FDFU. Thermostatically controlled loads such as air conditioning appliances and heaters are common examples of this type of flexible resources. Customers comfort should be taken into account when scheduling thermostatically controlled loads of the customers. As a result, they are not allowed to be fully controlled and synchronized with the variability needs of renewable resources.

Complementary flexible resources (CFR) are introduced as a third type which are able to be fully controlled and managed in order to meet the needs of both FDPV as well as FDFU. These resources can be fully managed and controlled since they have adjustable working power and working time. Storage resources such as batteries, ultra-capacitors, and thermal storage are three examples of CFRs.

III. Problem Formulation

In this section, the process of matching flexibility bids with flexibility offers are described from the viewpoint of the LFMO. The LFMO solves an optimization-based problem to match the selling offers with the buying bids. As previously mentioned, the main objective of the LFM is to minimize the difference between the actual flexibility demand and the amount of flexibility demand that will be met in the LFM.

$$\min D_{i,t}^{up} - \sum_{j} D_{i,j,t}^{up} + D_{i,t}^{dn} - \sum_{j} D_{i,j,t}^{dn} \qquad (1)$$

Where, $D_{i,t}^{up}$ and $D_{i,t}^{dn}$ are parameters implying the upward and downward flexibility demand required for player i at trading time slot t. In comparison, $D_{i,j,t}^{up}$ and $D_{i,j,t}^{dn}$ are variables denoting the amount of flexibility demand of buyer i that will be met by the flexibility production of seller j at time slot t in the proposed LFM. As stated before, the flexibility demand is divided into two types, FDPV and FDFU:

$$D_{i,t}^{up} = D_{i,t}^{up,FDPV} + D_{i,t}^{up,FDFU} \qquad (2)$$

$$D_{i,t}^{dn} = D_{i,t}^{dn,FDPV} + D_{i,t}^{dn,FDFU} \qquad (3)$$

$$D_{i,j,t}^{up} = D_{i,j,t}^{up,FDPV} + D_{i,j,t}^{up,FDFU} \qquad (4)$$

$$D_{i,j,t}^{dn} = D_{i,j,t}^{dn,FDPV} + D_{i,j,t}^{dn,FDFU} \qquad (5)$$

The minimization-based problem should be restricted to the following power balancing-related equations:

$$D_{i,j,t}^{up,FDFU} + D_{i,j,t}^{up,FDPV} = P_{j,i,t}^{up,PFR} + P_{j,i,t}^{up,FRFU} + P_{j,i,t}^{up,CFR} \quad (6)$$

$$D_{i,j,t}^{up,FDPV} \leq P_{j,i,t}^{up,PFR} + P_{j,i,t}^{up,CFR} \quad (7)$$

$$D_{i,j,t}^{dn,FDFU} + D_{i,j,t}^{dn,FDPV} = P_{j,i,t}^{dn,PFR} + P_{j,i,t}^{dn,FRFU} + P_{j,i,t}^{dn,CFR} \quad (8)$$

$$D_{i,j,t}^{dn,FDPV} \leq P_{j,i,t}^{dn,PFR} + P_{j,i,t}^{dn,CFR} \quad (9)$$

Where $P_{j,i,t}^{up,PFR}$, $P_{j,i,t}^{up,FRFU}$, and $P_{j,i,t}^{up,CFR}$ are variables indicating the PFR, FRFU, and CFR flexibility production sold from player j to player i at t, respectively. Eq. (6) and (8) state that FDFU and FDPV flexibility demand should be met by all types of flexible resources whereas (7) and (9) express that PFR and CFR are the only resources that should be deployed to fulfill FDPV flexibility requirements.

Capacity-related restrictions are the other constraints associated with the LFMO optimization problem:

$$\sum_j (D_{i,j,t}^{up,FDPV} + D_{i,j,t}^{up,FDFU}) \leq D_{i,t}^{up} \quad (10)$$

$$\sum_i (P_{j,i,t}^{up,PFR} + P_{j,i,t}^{up,FRFU} + P_{j,i,t}^{up,CFR}) \leq P_{j,t}^{up} \quad (11)$$

$$P_{j,t}^{up} = P_{j,t}^{up,PFR} + P_{j,t}^{up,FRFU} + P_{j,t}^{up,CFR} \quad (12)$$

$$P_{j,i,t}^{up,FRFU} \leq P_{j,t}^{up,FRFU}, P_{j,i,t}^{up,CFR} \leq P_{j,t}^{up,CFR} \quad (13)$$

$$P_{j,i,t}^{up,PFR} = u_{j,i,t}^{up} P_{j,t}^{up,PFR} \quad (14)$$

$$D_{i,j,t}^{up,FDPV} \leq D_{i,t}^{up,FDPV}, D_{i,j,t}^{up,FDFU} \leq D_{i,t}^{up,FDFU} \quad (15)$$

$$\sum_j (D_{i,j,t}^{dn,FDPV} + D_{i,j,t}^{dn,FDFU}) \leq D_{i,t}^{dn} \quad (16)$$

$$\sum_i (P_{j,i,t}^{dn,PFR} + P_{j,i,t}^{dn,FRFU} + P_{j,i,t}^{dn,CFR}) \leq P_{j,t}^{dn} \quad (17)$$

$$P_{j,t}^{dn} = P_{j,t}^{dn,PFR} + P_{j,t}^{dn,FRFU} + P_{j,t}^{dn,CFR} \quad (18)$$

$$P_{j,i,t}^{dn,FRFU} \leq P_{j,t}^{dn,FRFU}, P_{j,i,t}^{dn,CFR} \leq P_{j,t}^{dn,CFR} \quad (19)$$

$$P_{j,i,t}^{dn,PFR} = u_{j,i,t}^{dn} P_{j,t}^{dn,PFR} \quad (20)$$

$$D_{i,j,t}^{dn,FDPV} \leq D_{i,t}^{dn,FDPV}, D_{i,j,t}^{dn,FDFU} \leq D_{i,t}^{dn,FDFU} \quad (21)$$

Eq. (10) and (16) discuss that the total flexibility power bought from the LFM to meet the flexibility demand of buyer i should not exceed the flexibility demand submitted by this player. Similarly, the total flexibility sold by seller j should not exceed its maximum capacity submitted to the LFM, denoted by (11) and (17).

Eq. (12) and (18) show that the upward and downward flexibility production are provided by PFR, FRFU, and CFR resources. Besides, according to (13) and (19), the production capacity of the FRFU and CFR resources sold from j to i should be lower than their maximum limits submitted by the player j to the LFM. As stated before, the working power of PFR cannot be controlled. Thus the LFMO should either utilize their full capacities or do not deploy them at all. Eq. (14) and (20) explain this statement in shape of equations. In these equations, $u_{j,i,t}^{up}$ and $u_{j,i,t}^{dn}$ are binary variables determining the status of the PFRs.

Finally, (15) and (21) restrict the maximum amount of FDPV and FDFU traded from seller j to buyer i in the LFM based on their offered amount submitted by player i.

IV. Case Study and Numerical Results

The case study consists of ten players, five flexibility sellers (j1,…,j5) and five flexibility buyers (i1,…,i5). Fig. 3 shows the share of flexible resources that each seller submits to the LFM.

The players are assumed to submit their available flexibility production and the flexibility demand for the next four 15-min time slots. Fig. 4 gives information about the flexibility demand submitted by flexibility buyers. As can be seen in the figures, sellers are supposed to have various types of flexible resources (Fig. 3). In addition, all of the buyers offer both types of flexibility demand, FDPV and FDFU (Fig. 4). Upward flexibility was regarded as the only type of flexibility that sellers and buyers offer for the next hour.

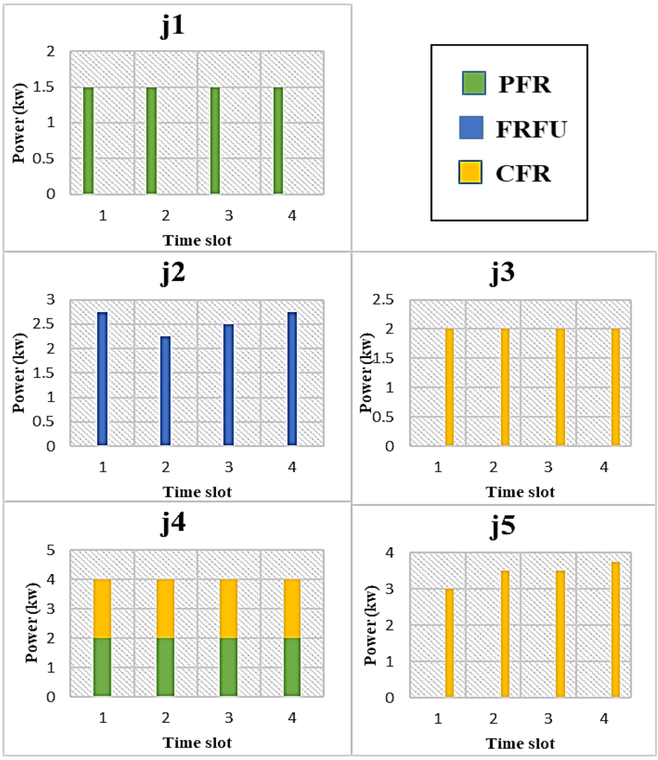

Fig. 3. The share of different types of flexible resources for the case study

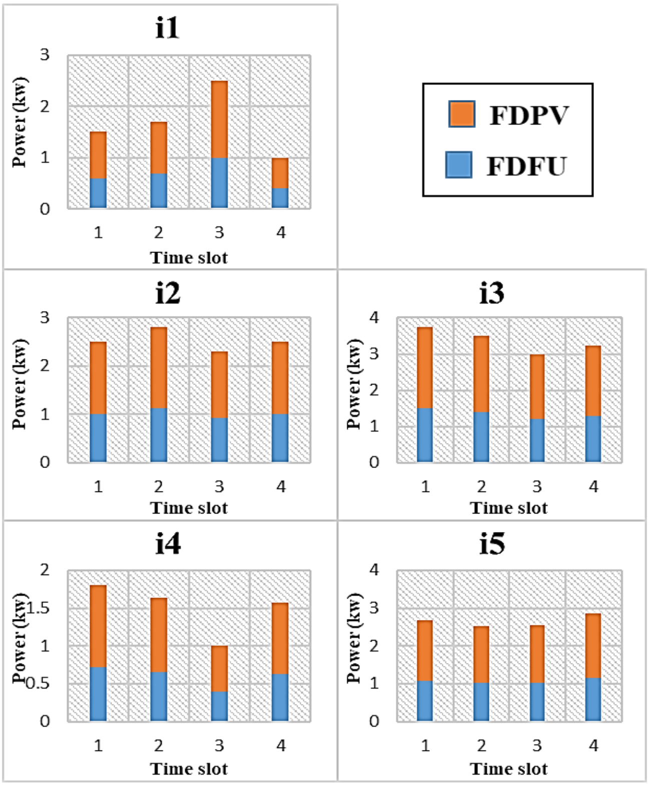

Fig. 4. The share of different types of demand for the case study

Furthermore, the proposed LFM clearing model, regarding (1)-(21) has solved for the test. The results state that the whole amount of flexibility demand in each time slot was supplied by the local flexibility production. Also, the results associated with the trading structure of the proposed LFM are illustrated in Fig. 5 and Fig. 6. These figures (Fig. 5 and Fig. 6) show state the trading amount as well as time slots in which the local flexibility trading occurs. For example, i1 bought 0.6 kW from j1 at time slot 6 in order to meet its FDFU need (Fig. 5).

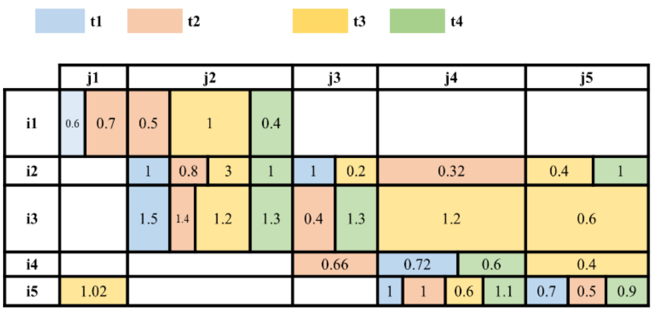

Fig. 5. The structure of the LFM for meeting FDFU need

As it can be seen from the figures (Fig. 5 and Fig. 6), the proposed local market has the acceptable liquidity since all of the local flexibility sellers participate in meeting FDFU and FDPV, except for seller j4 whose type of flexible resource prevents it from supplying FDPV need.

In order to analyze the participation of sellers in the proposed LFM, we define a factor named "flexibility surplus ratio" (FSR), which yields from the following:

$$FSR_{j,t} = \frac{P_{j,t}^{up} - \sum_i (P_{j,i,t}^{up,PFR} + P_{j,i,t}^{up,FRFU} + P_{j,i,t}^{up,CFR})}{P_{j,t}^{up}} \quad (22)$$

The lower amount of FSR for a seller denotes that more flexible capacities were sold to the LFM. The flexibility surplus ratio of each seller at each time slot was calculated and depicted in Fig. 7.

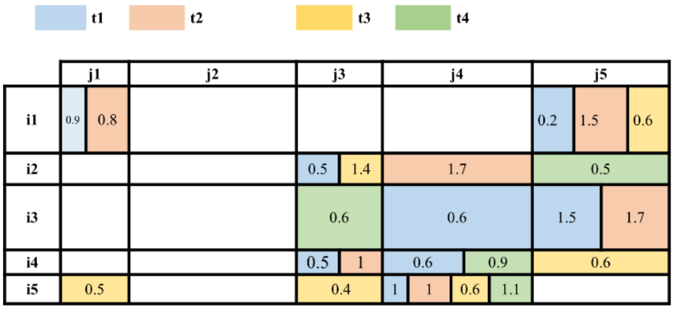

Fig. 6. The structure of the LFM for meeting FDPV need

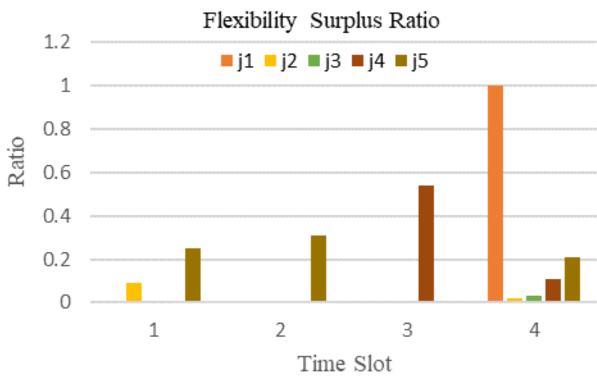

Fig. 7. Flexibility surplus ratio for the sellers participating in the LFM

Fig. 7 states that j1 with PFR flexibility production has the highest flexibility surplus ratio. This means that the FFR sources which are less flexible compared to the other sources, were the last priority when supplying flexibility demand at time slot 4. The surplus ratio for j4 shows that FRFU can also lead to huge participation in the LFM. Moreover, j3 which has pure CFR resources has the lowest surplus ratio at all of the time slots in the proposed LFM.

V. Conclusion

Flexible energy resources can be regarded as very potential solution to manage the impacts resulting from the connection of large amount of distributed renewable resources in the distribution systems. In order to deploy the maximum potential of flexible resources, a suitable trading structure needs to be applied in order to integrate these resources and enable small-scale customers to trade flexibility with each other. In this regard, this paper proposed a local flexibility market in which small customers and prosumers can trade flexibility with each other. Flexibility buyers can purchase flexibility from the local market with the target to avoid penalty costs resulted from their intermittent resources while flexibility sellers are given opportunity to make profits in the local market. The proposed flexibility local market also helps TSOs and DSOs because the local customer-level flexibility need can be provided by the local customer-level resources. Finally, the proposed trading model was implemented for a small test system with ten local players. The results showed an acceptable degree of liquidity for the proposed market.

VI. ACKNOWLEDGEMENT

This work was supported by FLEXIMAR -project (Novel marketplace for energy flexibility) which is funded by Business Finland and Finnish companies (https://www.univaasa.fi/en/research/projects/fleximar).

REFERENCES

[1] H. Khajeh, H. Laaksonen, S. Gazafroudi, and M. Shafie-khah, “Towards flexibility trading at TSO-DSO-customer levels: a review,” 2019.

[2] M. Khoshjahan, M. Moeini-Aghtaie, and M. Fotuhi-Firuzabad, “Developing new participation model of thermal generating units in flexible ramping market,” IET Gener. Transm. Distrib., 2019.

[3] A. Paudel, K. Chaudhari, C. Long, and H. B. Gooi, “Peer-to-Peer Energy Trading in a Prosumer-Based Community Microgrid: A Game-Theoretic Model,” IEEE Trans. Ind. Electron., vol. 66, no. 8, pp. 6087–6097, 2018.

[4] Y. Liu, L. Xiao, G. Yao, and S. Bu, “Pricing-based demand response for a smart home with various types of household appliances considering customer satisfaction,” IEEE Access, vol. 7, pp. 86463–86472, 2019.

[5] A. Ramos, C. De Jonghe, V. Gómez, and R. Belmans, “Realizing the smart grid’s potential: Defining local markets for flexibility,” Util. Policy, vol. 40, pp. 26–35, 2016.

[6] B. A. Bremdal, P. Olivella-Rosell, J. Rajasekharan, and I. Ilieva, “Creating a local energy market,” CIRED-Open Access Proc. J., vol. 2017, no. 1, pp. 2649–2652, 2017.

[7] T. Pinto, R. Faia, M. A. F. Ghazvini, J. Soares, J. M. Corchado, and Z. M. A. do Vale, “Decision support for small players negotiations under a transactive energy framework,” IEEE Trans. Power Syst., 2018.

[8] I. Praça, C. Ramos, Z. Vale, and M. Cordeiro, “MASCEM: a multiagent system that simulates competitive electricity markets,” IEEE Intell. Syst., vol. 18, no. 6, pp. 54–60, 2003.

[9] T. Morstyn, A. Teytelboym, and M. D. McCulloch, “Designing Decentralized Markets for Distribution System Flexibility,” IEEE Trans. Power Syst., vol. 34, no. 3, pp. 2128–2139, 2018.

[10] C. Kok, J. Kazempour, and P. Pinson, “A DSO-level contract market for conditional demand response,” in 13th IEEE PES PowerTech Conference, 2019.

[11] H. Khajeh, A. A. Foroud, and H. Firoozi, “Robust bidding strategies and scheduling of a price-maker microgrid aggregator participating in a pool-based electricity market,” IET Gener. Transm. Distrib., vol. 13, no. 4, pp. 468–477, 2018.

[12] M. A. Matos et al., “Control and management architectures,” Smart grid Handb., pp. 1–24, 2016.

[13] W. Tushar, T. K. Saha, C. Yuen, D. Smith, and H. V. Poor, “Peer-to-Peer Trading in Electricity Networks: An Overview,” IEEE Trans. Smart Grid, 2020.

[14] Z. Zhang, R. Li, and F. Li, “A Novel Peer-to-Peer Local Electricity Market for Joint Trading of Energy and Uncertainty,” IEEE Trans. Smart Grid, 2019.