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Flexibility Participation by Prosumers in Active Distribution Network Operation

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***Abstract*—This paper investigates prosumers' flexibility provision for the optimal operation of active distribution networks in a transactive energy (TE) market. From a prosumer point of view, flexibility can be provided to operators using renewable energy resources (RES) and demand response (DR) through home appliances with the ability to modify their consumption profiles. In the TE market model, the distribution system operator (DSO) is responsible for market-clearing mechanisms and controlling the net power exchange between the distribution network and the upstream grid. The contribution of this work is the enhancement of a strategy to reduce operational costs of an active distribution network by using prosumers' flexibility provision through an aggregator or a smart building coordinator. To this end, a TE market for both energy and flexibility trading at distribution networks is presented, demonstrating the possibility to fulfill DSO requirements through the flexibility contributions in the day-ahead (DA) and real-time (RT) markets.**

Index Terms—Energy management system, Flexibility provision, Prosumers flexibility, Smart homes, Transactive energy.

I. INTRODUCTION

In the presence of renewable energy sources (RES) at residential level, active consumers will act as prosumers, which means active producers while maintaining the consumer role [1]. In this case, the participation of prosumers in energy and flexibility markets would better cover the investment cost and increase RES penetration at residential levels. However, the increase in RES poses a challenge to the distribution system operator (DSO) in terms of system reliability and security due to RES intermittency. Furthermore, substantial electrical loads (electric vehicles, heat pumps, among others) are more common, leading to increased load fluctuations in distribution systems [2]. To address these issues, DSOs have investigated the application of a range of solutions, including energy flexibility, demand response (DR), and energy efficiency initiatives [3]-[4].

Nowadays, electricity markets do not allow the participation of small prosumers, as they are not large enough to participate directly. Hence, the services of an aggregator are necessary for prosumers to participate in the electricity markets. In addition, smart buildings are a potential source of demand-side energy flexibility, thus being able to improve the flexibility of the entire system [5].

In [6], a research project is presented in which a new way of managing the addition of prosumers to the distribution network is proposed. It presents a model called "DEMAND," which lacks a physical aggregator, using instead a Virtual Aggregation Environment (VAE) to exchange information between prosumers in a smart grid. Prosumer flexibility management, "Flex4Grid" (F4G), and the effect of dynamic pricing on customer responsiveness, "Pilot Critical Peak Tariff Project", are two research projects addressing the area of prosumer flexibility management [7]. The projects' cooperation allows the utilization of modern smart grid infrastructures and the evaluation of prosumers flexibility management in practice.

In [8], a non-cooperative framework for distributed consumer coordination is proposed, in which distributed consumers can schedule and share excess energy with the grid. Furthermore, to alleviate the parallel bilateral communications between consumers and the aggregator, a virtual power plant communicates with the aggregator on the consumers' side to take advantage of its consumption, generation, and storage flexibilities.

Prosumers have been used to address the balancing services to the Transmission System Operator (TSO), devising a strategy for coordinating these prosumers to satisfy the TSO's energy flexibility requests [9]. A bid optimization strategy in which network constraints exist to support the participation of prosumers aggregators in multiple electricity markets, in which the aggregators' profits are maximized, is shown in [10]. A solution to support the participation of an aggregator with small prosumers in energy and tertiary reserve markets is presented in [11]. It proposes a stochastic two-stage optimization model to exploit the load and generation flexibility of the prosumers in the day-ahead and real-time (RT) markets. Ref. [12] presents a two-level hierarchical model predictive control (MPC) model to support aggregators of prosumers that deliver energy and reserve through flexible resource control.

Other approaches propose a quantitative flexibility model in which prosumers' integrated energy is dispatched, considering distributed energy resources (DERs) and grid constraints [13]. These approaches aim to improve the speed of operation, reduce the variable dimension of DERs, and obtain the maximum benefit from the purchase and sale of electricity, while maintaining the secure operation of the grid. An intelligent multi-agent control system with heuristic optimization is proposed in [14] for energy and comfort management in an integrated building and micro-grid system. Furthermore, a model for aggregators' flexibility provision in distribution networks is presented in [15].

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The flexibility provided by the prosumers is an interesting option to be procured in the flexibility market. In addition, the aggregated flexibility that can be procured from the active end-users benefiting from an home energy management system (HEMS) is another option to be considered. Therefore, this work presents a TE market for both energy and flexibility trading at distribution networks. The main contribution of this work is the enhancement of a strategy to reduce operational costs of an active distribution network by using prosumers' flexibility provision through an aggregator or a smart building coordinator.

The remainder of this paper is organized as follows. Section II describes the participation of prosumers in the system flexibility requirements by the DSO. Then, the proposed transactive energy (TE) model is presented in Section III. Next, a case study is reported in Section IV. Finally, conclusions are drawn in Section V.

II. PROSUMERS' PARTICIPATION IN FLEXIBILITY PROVISION

A smart building (SB) is regarded as a controllable load. SBs inspect, examine, and optimize comfort-related devices, considering customer preferences and other important information. As a result, the SB may submit to the DSO the load curtailment and/or load shifting to provide flexibility to the system. Aggregators emerge as an intercommunication between small users and the DSO to make DR programs available and receive rewards. In addition, these aggregators provide flexibility to the DSO through the efficient use and optimization of energy resources.

Fig. 1 depicts the communication between the DSO and prosumers (aggregators and SBs), where the DSO communicates distribution system flexibility requirements to prosumers. In addition, end-users can voluntarily register devices to participate in the provision of flexibility by receiving monetary compensation if they modify their base demand profile [15]. Furthermore, end-users can configure their preferences in terms of allowed switching times, expected remuneration, and priority of devices available for activation. Aggregators/SBs use a flexible management system on DR-capable devices to schedule such devices to provide a decrease, increase or change in demand (without sacrificing user comfort and preferences) to fulfill DSO flexibility requirements. This process is carried out through mutual communication with the supervisor and the network coordinator.

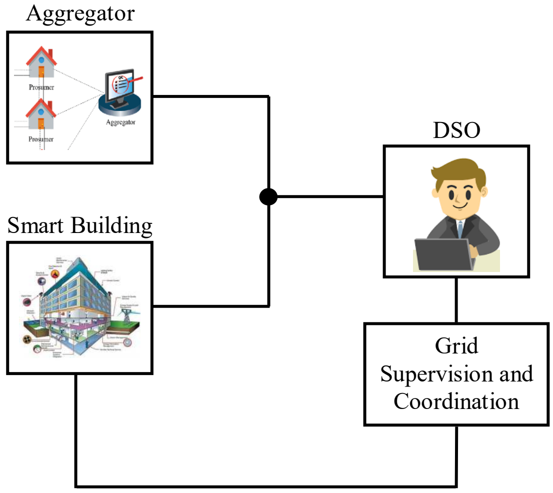

Fig. 1. Flexibility requested by the DSO.

III. PROPOSED TE MODEL

In this work, the flexibility requested by the DSO needs to be served by the prosumers in such a way as to minimize the procurement cost. To do so, a TE market is designed to provide the flexibility requested by the DSO.

The function to be minimized is shown in (1), which comprises the production costs, start-up and shut-down costs, unserved energy costs, storage degradation and discharge costs, and DSO revenues from the sale and purchase of energy to the wholesale.

The first term comprises the production and start-up and shut-down generation costs. The second term includes storage degradation and discharge costs. The third term is the non-served energy cost. Finally, the fourth term represents the DSO's revenues. α_i, sdc_i, suc_i are the fixed, start-up, and shut-down costs of generator i, respectively, $C_{s,t}^{deg}$ and $C_{s,t}^{dis}$are the degradation and discharge costs of the BESS s respectively, $C_i^{ems}$is the cost for energy not supplied, and π^t is the local marginal price at the interchange point.

$$Min \sum_{t\in T}\left(\begin{array}{l}\sum_{i\in I}\left(\alpha_i u_{i,t}+\sum_{k\in Lk} kg_{i,k}\Delta p_{i,k,t}+sdc_i z_{i,t}+suc_i y_{i,t}\right)\\+\sum_{s\in S}\left(C_{s,t}^{\deg} pc_{s,t}+C_{s,t}^{dis} pd_{s,t}\right)+\sum_{b\in B} C_b^{ens} pens_{b,t}\\-\sum_{n\in N}\pi_t NP_{n,t}\end{array}\right) \tag{1}$$

subject to:

$$\begin{array}{l}\sum_{i\in I} p_{i,t}+\sum_{p\in P} pv_{p,t}+\sum_{s\in S} pd_{s,t}+\sum_{b\in B} pens_{b,t}=\\\sum_{b\in B} D_{b,t}+\sum_{s\in S} pc_{s,t}+\sum_{l\in L} P_{l,t}^{Loss}+\sum_{n\in N} NP_{n,t}\\\forall t\in T\end{array} \tag{2}$$

$$p_{i,t}=\sum_{k\in Lk}\Delta p_{i,k,t}\ ;\ \forall i\in I,\forall k\in Lk,\forall t\in T \tag{3}$$

$$0\le \Delta p_{i,k,t}\le \frac{p_i^{Max}}{Lk}\ ;\ \forall i\in I,\forall k\in Lk,\forall t\in T \tag{4}$$

$$-p_{i,t-1}\le u_{i,t-1}RU_i+y_{i,t}RSU_i\ ;\ i\in I,\forall t\in T \tag{5}$$

$$-p_{i,t}+p_{i,t-1}\le u_{i,t}RD_i+z_{i,t}RSD_i\ ;i\in I,\forall t\in T \tag{6}$$

$$u_{i,t}P_i^{Min}\le p_{i,t}\le u_{i,t}P_i^{Max}\ ;\ \forall i\in I,\forall t\in T \tag{7}$$

$$u_{i,t}=p_i^{on-off}\ ;\forall i\in I,0\le t\le L_i^{up,\min}+L_i^{down,\min} \tag{8}$$

$$\sum_{\tau=t-Pg_i^{UP}+1}^{t} y_{i,t}\le u_{i,t}\ ;\ \forall i\in I,\forall t\le L_i^{Up,Min} \tag{9}$$

$$\sum_{\tau=t-Pg_i^{Down}+1}^{t} z_{i,t}\le 1-u_{i,t}\ ;\ \forall i\in I,\forall t\le L_i^{Down,Min} \tag{10}$$

$$y_{i,t}+z_{i,t}\le 1\ ;\forall i\in I,\forall t\in T \tag{11}$$

$$u_{i,t} = u_{i,t-1} + y_{i,t} - z_{i,t}\,; \forall i \in I, \forall t \in T \tag{12}$$

$$u_{i,t} \in \{0,1\}, y_{i,t} \in \{0,1\}, z_{i,t} \in \{0,1\}\,; \forall i \in I, \forall t \in T$$

$$PD_s^{Min} \le pd_{s,t} \le PD_s^{Max}\,;\ \forall s \in S, \forall t \in T \tag{13}$$

$$PC_s^{Min} \le pc_{s,t} \le PC_s^{Max}\,;\ \forall s \in S, \forall t \in T \tag{14}$$

$$SOC_{s,t} = SOC_{s,t-1} + \eta_s^{BESS} pc_{s,t} - \frac{pd_{s,t}}{\eta_s^{BESS}} \qquad \forall s \in S, \forall t \in T \tag{15}$$

$$SOC_s^{Min} \le SOC_{s,t} \le Cap_s\,;\ \forall s \in S, \forall t \in T \tag{16}$$

$$SOC_{s,1} = SOC_{s,T}\,;\ \forall s \in S \tag{17}$$

$$NP^{Min} \le NP_{n,t} \le NP^{Max}\,;\ \forall t \in T \tag{18}$$

$$\begin{aligned} P_{l,t} = \sum_{b \in B} PTDF_{b,l} \Bigg(& \sum_{i \in I} Cg_{b,i} p_{i,t} - D_{b,t} + pens_{b,t} \\ & + \sum_{p \in P} Cp_{b,p} PV_{p,t} - \sum_{n \in N} Cn_{b,n} NP_{n,t} \\ & + \sum_{s \in S} Cb_{b,s} \left(pd_{s,t} + pc_{s,t} \right) - \left| 0.5 Ck_{b,l} P_{l,t}^{Loss} \right| \Bigg) \end{aligned} \tag{19}$$

$$-P_l^{Max} \le P_{l,t} + P_{l,t}^{Loss} \le P_l^{Max}\,;\ \forall l \in L \tag{20}$$

$$P_{l,t} = P_{l,t}^{+} - P_{l,t}^{-}\ ;\ \forall l \in L \tag{21}$$

$$\sum_{r \in LR} \Delta P_{l,r,t} = P_{l,t}^{+} + P_{l,t}^{-}\ ;\ \forall r \in Lr, \forall l \in L, \forall t \in T \tag{22}$$

$$0 \le \Delta P_{l,r,t} \le \frac{P_l^{Max}}{Lr}\,;\ \forall r \in Lr, \forall l \in L, \forall t \in T \tag{23}$$

$$P_{l,t}^{L} = \left(\frac{G_l}{B_l^2} \right) \sum_{r \in Lr} \zeta_{l,r} \Delta P_{l,r,t}\ ; \quad \forall r \in Lr, \forall l \in L, \forall t \in T \tag{24}$$

$$P_{l,t}^{+}, P_{l,t}^{-} \ge 0\,;\ \forall l \in L \tag{25}$$

$$L_i^{Up,Min} = \max\left(0, \min\left(\left(p_i^{Up} - p_i^{Up,init}\right) p_i^{on-off}\right)\right); \quad \forall i \in I \tag{26}$$

$$L_i^{Down,Min} = \max\left(\min\left(\left(p_i^{Down} - p_i^{Down,init}\right)\left(1 - p_i^{on-off}\right)\right)\right) \quad \forall i \in I \tag{27}$$

$$\zeta_{l,r} = (2r-1)\left(\frac{P_l^{Max}}{Lr}\right)\ ;\ \forall r \in Lr, \forall l \in L \tag{28}$$

In this work, the following group of sets are considered: T is the set of time, I is the set of generators, P is the set of photovoltaic systems, N is the set of energy exchange points, S is the set of battery energy storage system (BESS), L is the set of lines, B is the set of buses, and Lk, Lr are the set of segments used for power and loss linearization, respectively.

Constraint (2) represents the system power balance, where $p_{i,t}$ is the output of generator i in period t, $pv_{p,t}$is the forecasted power of the p photovoltaic (PV) system in period t. Also, $pens_{b,t}$ is the energy not served of bus b in period t, $pd_{s,t}$ and $pc_{s,t}$ are the discharge and charge, respectively, of the BESS s in period t, $D_{b,t}$ is the forecasted demand of bus b in period t,$P_{l,t}^{Loss}$ are the losses of line l in period t, and $NP_{n,t}$ is the exchanged power with the main network in period t.

Equations (3)-(4) represent the linearization of the power cost curve, where $\Delta p_{i,k,t}$ is the active power produced by generator i in block k in period t, P_i^{Max} is the maximum power output of unit i, and Lk is the number of generation unit cost curve segments. Constraints (5)-(6) represent the generator's ramp rates, where RU_i is the ramp-up rate of unit i, RSU_i is the ramp start-up limit of unit i, RSD_i is the ramp shut-down limit of unit i, $u_{i,t-1}$, $y_{i,t}$and $z_{i,t}$ are the binary variables for generator scheduling. Constraint (7) represents the production limits, where P_i^{Min} is the minimum power output of unit i. Constraint (8) allows that in period $t = 1$ the minimum in-service and out-of-service time constraints are met, where $P_i^{Up,\ init}$ and $P_i^{Down,\ init}$ are the g unit's time has been on and off, respectively.

Constraints (9)-(10) represent the minimum up- and down- times, where $L_i^{Up,Min}$and $L_i^{Down,Min}$are the minimum up- and down- times, respectively, of unit i. In other words, the unit should remain in/out of service at time t if its start/stop before $p_i^{Up} - 1/p_i^{Down} - 1$ hours. The minimum generator up/down time constraints are taken from [16]. Constraints (11)-(12) preserve running, start-up, and shut-down status change logic. Constraints (13)-(14) impose the maximum and minimum discharge and charge limits, where pd_s^{Min} and pd_s^{Max} are the minimum and maximum discharge limits, respectively, and pc_s^{Min} and $pc_s^{Max}$are the minimum and maximum charge limits, respectively.

Constraint (15) represents the state of charge in the BESS, where $SOC_{s,t}$ is the state of charge of the BESS s in period t, $\eta_s^{BESS}$is the charge/discharge efficiency of the BESS s, $pc_{s,t}$ is the charge of the BESS s in period t, $pd_{s,t}$ is the discharge of the BESS s in period t. Constraint (16) represents the maximum and minimum limit of the state of charge of the BESS. Constraint (17) indicates that the state of charge of period one must be the same as that of period T. Constraint (18) represents the minimum and maximum limits of power exchange, where NP^{Max} and $NP^{Min}$are the maximum and minimum power exchanges with the grid, respectively.

Constraint (19) represents the power flows, where $PTDF_{b,l}$represent the element of node b and line l of the PTDF matrix, $Cg_{b,i}$, $Cb_{b,s}$, $Cp_{b,p}$, $Ck_{b,l}$, and $Cn_{b,n}$ are the generator-bus, PV-bus, storage-bus, branch-bus, and energy exchange incidence matrices, respectively, and $P_{r,l}^{Loss}$ is the loss on line l in period t. Constraint (20) represents the transmission limit, where P_l^{Max} is the active power capacity of line l. Constraints (21)-(25) model the transmission losses in a piecewise linear manner.

From (21)–(25), $P_{l,t}^{+}$ and $P_{l,t}^{-}$ represent the positive and negative power flow of line *l* in period *t*, respectively, $\Delta P_{l,r,t}$ is the power flow of line *l* in linear section *r* period *t*, Lr is the number of segments in the linearization, G_l is the conductance in the distribution line l,B_l is the susceptance of the distribution line *l* and $\zeta_{l,r}$ is the slope of the linear segment of the line *l.* The aggregator model in [15] is extended to incorporate SBs. The flexibility provided by the aggregator/SB is defined as the difference between the reference profile $P_{Base(t)}$, and the new scheduled profile $P_{Flex(t)}$, as follows:

$$F_{agg} = P_{Base(t)} - P_{Flex(t)} \tag{29}$$

Two types of loads are assumed: type *C* and type *E*. Type *C* loads consider heavier loads such as washing machines, clothes dryers, and dishwashers. Type *E* loads consider lighting systems, entertainment systems, and desktops. The baseline profile and the baseline profile after shifting are given as follows:

$$P_{Base(t)} = \sum_{c\in C} C_{Base(c,t)} + \sum_{e\in E} E_{Base(e,t)} \tag{30}$$

$$P_{Flex(t)} = \sum_{c\in C} C_{Flex(c,t)} + \sum_{e\in E} E_{Flex(e,t)} \tag{31}$$

where $C_{Base(c,t)}$ and $E_{Base(c,t)}$ are the reference power of devices *c* and *e,* in period *t*, $C_{Flex(c,t)}$ and $E_{Flex(c,t)}$ are the reference power of devices *c* and *e,* in period *t,* after shifting.

To maximize prosumer benefits, the objective function is modeled as a minimization of the payment to households for the mismatch of flexibility purchased by the DSO.

$$Min\left(\sum_{c\in C} \mathrm{Rem}_{C(c)} + \sum_{e\in E} \mathrm{Rem}_{E(e)}\right) \tag{32}$$

$$\mathrm{Rem}_{C(c)} = \begin{Bmatrix} C_{C(c)} & if \quad t_{start(c)} \neq t_{new(c)} \\ 0 & Otherwise \end{Bmatrix} \tag{33}$$

$$\mathrm{Rem}_{E(e)} = C_{E(e)} \sum_{t\in T} \left| E_{Base(e,t)} - E_{Flex(e,t)} \right| \tag{34}$$

The first term in (32) is the remuneration paid for the shifting of device *c*, while the second term is the monetary compensation for the change in the baseload profile of device type *e*. Both remunerations are based on distribution locational marginal prices (DLMP) [17].

The bi-level model structure is depicted in Fig. 2. In this model, the first level is responsible for minimizing the production costs of the distribution system, considering the technical constraints of storage, energy flows, power balance and technical constraints of the generators. The second level acts as a follower of the first one; at this level, the consumers' remunerations are maximized, considering their preferences and comfort.

The local marginal prices at each node can be derived from the results obtained by the DSO at the first level [17]. Given the DLMP, aggregators/SBs use them for economic energy scheduling.

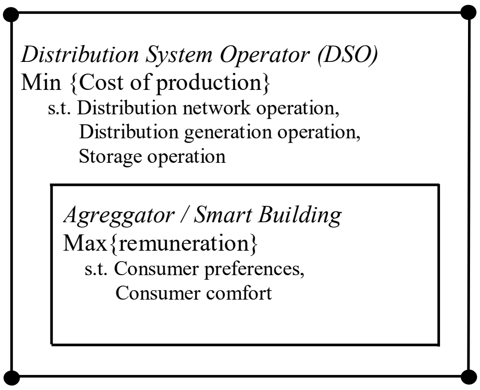

Fig. 2. Bi-level structure of the proposed model.

IV. CASE STUDY

The IEEE 16-bus system considered has 3 feeders, 16 nodes, 13 load points, 13 normally closed switches, and 3 normally opened switches. The complete network data is given in [19]. Fig. 3 shows the IEEE 16-bus distribution system single line diagram. There are three diesel generators on buses 7, 12, and 15, respectively. The data of the generation units is taken from [20]. Three PV systems are installed in nodes 6, 10, and 15, respectively. Nodes 4, 6, 7, 11, and 13 have aggregators. Finally, nodes 5, 8, 9, 10, 14, 15, and 16 have SBs. The optimization problem was implemented in GAMS [18], and CPLEX was used as the solver. Simulations were performed on a personal computer with an Intel Core i7, 2.5GHz, 16 GB RAM, and 64 bits.

To comprehensively analyze the response of end-users in the provision of flexibility requested by the DSO, the operation of storage units is not accounted for. In this work, the following assumptions are made:

1. A modern HEMS is installed at the end-users' side.
2. Both the aggregator and the SB are prepared to respond to a request for flexibility from the DSO.
3. The aggregator and the SB use the flexibility management system to reschedule load to match DSO flexibility requirements.
4. All distributed generation units are utility-owned and centrally scheduled by the DSO.
5. Up to 20% of each aggregator/SB load is shiftable on the DA market.
6. Between 3% and 5% of each aggregator/SB load is shiftable in a RT market.

Fig. 4 shows the demand and PV generation pattern per feeder. PV generation is similar for each of the three PV systems since solar radiation does not present a considerable variation from one installed point to another. The forecasted peak demand is around hours 16 to 20, with the maximum peak at hour 19. In contrast, the minimum demand is observed between hours 3 to 6.

Fig. 5 reports the DSO flexibility requirements for 15-minute periods. From Fig. 5, we can see that there are periods in which the DSO flexibility requirements are zero, for instance, hours 12 and 16. The maximum upward requirement is presented in the first hour of the day when the requirement reaches a value of 114 kW.

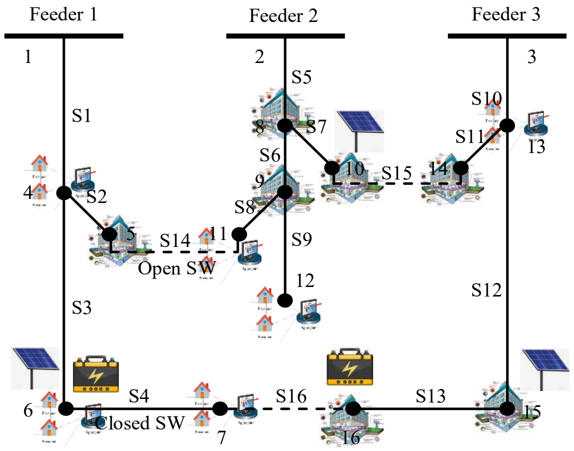

Fig. 3. IEEE 16-bus system considered in this paper.

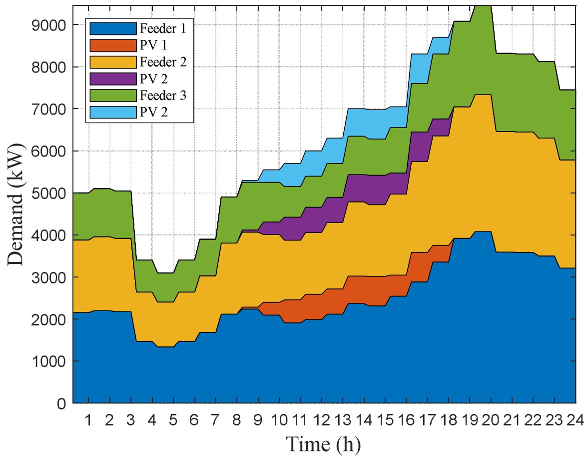

Fig. 4. Demand and photovoltaic generation in the distribution system.

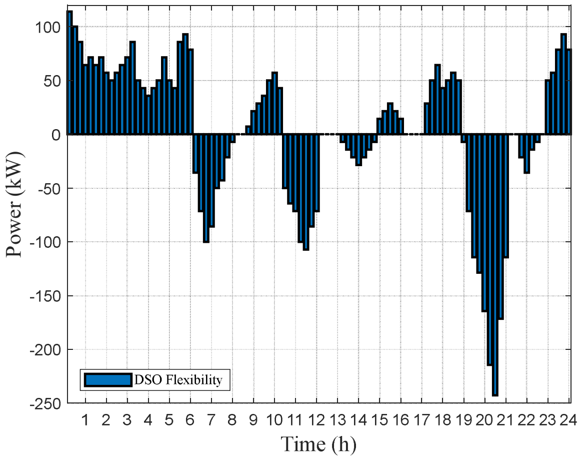

Fig. 5. Flexibility requested by the DSO.

Moreover, the maximum downward requirement is presented between 20 to 21 hours, with a value of 242 kW. Flexibility requirements must be met through DA and RT flexibility, with the help of aggregators and SBs by scheduling and load shifting.

Fig. 6 provides the day-ahead and RT market prices. The prices were taken for node "PIT5_7_N001" on January 29, 2022, 0. Real-time prices have been sampled at 15-minute intervals [21].

DA prices show a high cost in two periods, between hours 6-7 and 18-20, and a low period in hours 12-14, while RT price maintains a balanced pattern with a more expensive 5-hour period between hours 18-23.

Fig. 7 depicts DA flexibility provided by prosumers through the aggregator and SBs. A large contribution of flexibility to meet the DSO requirements is achieved in DA because the heaviest loads (type *C*) are scheduled.

Fig. 8 show the RT contribution to the DSO flexibility requirements, which as expected is much lower than DA's contributions. In RT operation, it is more difficult to achieve a substantial load shifting to meet the DSO requirements, so at this stage it is necessary a load reprogramming in which loads of lesser magnitude enter around 0.2 to 1 kW, such as lighting system, televisions, among others.

A peak of negative flexibility is observed from hour 18 to 21 (periods with the highest load and highest prices); this leads to shifting load to periods with lower demand, such as periods 0 to 6, in which the load must be increased to meet the flexibility requirements of the DSO. As a result, the DSO requirements are met with the sum of DA and RT contributions. The largest contribution of the aggregator and SB to meet the DSO requirements is in the DA. Indeed, in the DA it is easier to move large loads at different times of the day (e.g., washing machine, clothes dryer, dishwasher, among others).

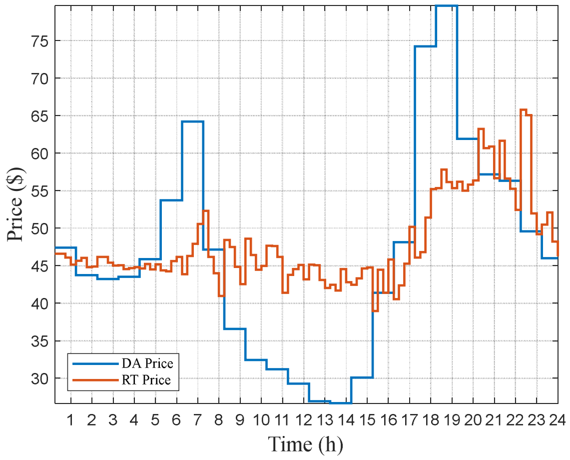

Fig. 6. DA and RT market prices.

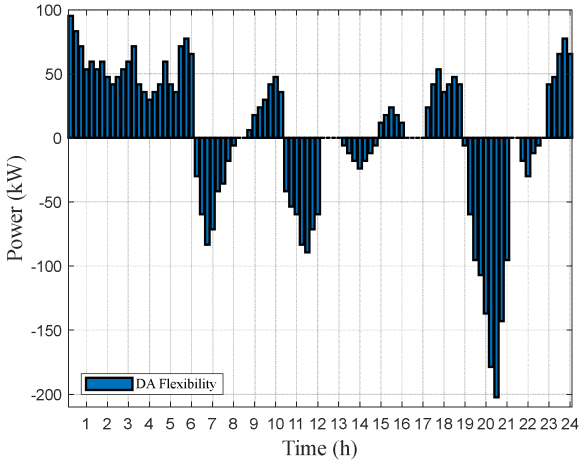

Fig. 7. Day-ahead flexibility provided by aggregators and smart buildings.

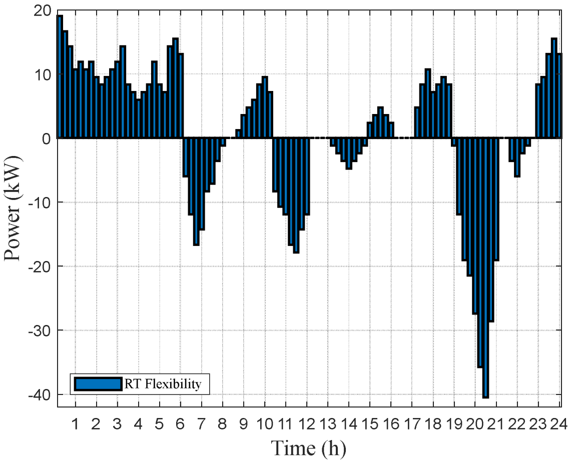

Fig. 8. RT flexibility procurement by aggregators and smart buildings.

V. CONCLUSION

In this work, aggregators and SBs, working together with prosumers, contributed to meet the flexibility requirements imposed by the DSO. As a result, prosumers could respond to a DSO flexibility request by reducing operating costs and maximizing end-user remunerations, considering also their preferences and conveniences. It was possible to fulfill the DSO requirements through the contributions of flexibility in the DA and RT markets. Up to 20% of each aggregator/SB load was shiftable on the DA, while in RT, only between 3% and 5%. Hence, the largest contribution of flexibility was acquired in the DA, while a smaller part came from RT contribution. Furthermore, aggregators and SBs were responsible for scheduling and reprogramming end-user devices with capabilities to decrease, increase or shift the load to other day periods.

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