Two-Stage Secure Bottom-Up Load Coordination Mechanism in Distribution Grids

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***Abstract*— Demand-side flexibility as a new source of ancillary services is attracting growing attention. Aggregation and coordination mechanisms are needed to efficiently use the demand side flexibility. This paper proposes a new secure two-stage bottom-up coordination mechanism that ensures the quality of service (QoS) for customers and facilitates improved services for both distribution and transmission system operators. In the first stage of the proposed method, the interaction between aggregators and controllable loads is addressed. In the second stage, the interactions between the DSO and aggregators are addressed. Commitments of the aggregators to follow their scheduled power in the electricity market are also taken into account in the proposed framework. The proposed method is applied to a test system with two areas supplied by two transformers with some uncontrollable loads, 70 PV/battery setups, and 80 heating systems supplied by heat pumps (HP) that are in contract with two aggregators. Simulation results highlight the effectiveness of the proposed method in preventing transformers' overload and reducing their loading by up to 27% while increasing the total electricity cost of customers with controllable devices by about 4.6%.**

Keywords—Demand side management, load coordination mechanisms, distribution grid services, secure coordination.

I. INTRODUCTION

The trend towards smart grids, as opposed to the traditional centralized approach to generating electricity, has resulted in a rise in the number of Distributed Energy Resources (DERs). These DERs comprise small-scale generation units owned by prosumers, flexible loads, and storage devices. The integration of a significant amount of renewables and DERs alongside the trend toward electrification of different sectors such as heat and mobility could make it challenging for DSOs to supply their demand due to technical issues such as transformers and lines overloading or voltage drop. To avoid or minimize excessive infrastructure investments, there is a need for creative operational strategies to enable DSOs to use DERs in their grids and provide secure and reliable services. Demand response management systems [1] designed for managing controllable devices and appliances are one of the solutions that can be supported and enhanced by the smart energy operating systems (SE-OS) [2] concept.

From the power system's perspective, individual controllable devices do not count for significant capacity in the system, making it impractical and unprofitable for the Transmission System Operator (TSO) or DSOs to communicate with each one separately. In fact, due to the complexity of the communication and transactional costs, individual controllable devices or prosumers are not able to directly participate in the wholesale markets or ancillary service programs and benefit the TSO and DSO directly [3]. To address this, devices are combined and managed by aggregators enabling coordinated management of resources and optimization of their operation. These devices could be located in different DSO grids. The aggregator's, communicating with the devices can enhance the devices' visibility to the power system, providing an opportunity for the aggregator to exploit their flexibility and participate in ancillary service markets [4]. In turn, the device owners benefit from rewards or ultimately lower energy bills for the consumers. One of the services aggregators can offer to the DSO is supporting the TSO by providing balancing services. Introducing new participants with DER resources and controllable devices to the local flexibility markets or traditional electricity markets can enhance competition, and provide the flexibility needed to integrate new variable capacities based on Renewable Energy Sources (RES) technology. They would also strengthen the DSO services and ensure reliable quality of service to the end users. Additionally, DERs and controllable devices are expected to provide grid-support functions and a range of autonomous commands to support the grid [5]. This is why secure communication and algorithms are paramount to consider during the design and deployment of new devices and DERs.

Load coordination mechanisms have been widely studied in the literature. From the viewpoint of structure and framework, studies can be categorized as centralized (e.g. [6]), decentralized (e.g. [7]), and distributed methods (e.g. [8]). Distributed methods combine the features of centralized and decentralized methods by having a centralized aggregator that coordinates devices while each load is equipped with control capabilities. Packetized Energy Management (PEM) is one of the recently introduced distributed coordination methods. PEM has been developed in [9] that improves upon the assumption that each load stochastically requests an energy packet from the aggregator based on the load's local state variables. The proposed approach, referred to as "packetized direct load control", assumed exact knowledge of the number of packetized loads at any given time, that one could queue up requests for synchronous allocation. Under PEM, the load makes grid access requests (GARs) under a generalized *need for energy* device state that has been applied for EVs, TCLs, and batteries. The PEM coordinator then either grants or denies each stochastic grid access request based on the tracking error for a power reference signal that is representative of grid and/or market conditions. That is, PEM represents a privacy-aware, asynchronous, and stochastic, bottom-up control scheme for many different switching loads, [10][11]. Considering the advantages of the PEM approach, this paper proposes a new load coordination mechanism inspired by the PEM. The main contribution of the proposed method compared to the PEM are:

- While the PEM is focused on the interaction of one aggregator and devices at one area in the grid, the proposed method in this paper considers the possibility of the presence of several aggregators in several areas using a two-stage bottom-up aggregation method;
- The proposed method is adapted with optimal control strategies at the customer level instead of the sub-optimal method in the PEM.

The organization of the paper is as follows: section II provides an overview of the problem definition and assumptions. Section III presents the proposed framework. Section IV describes the case study and simulation results and section V concludes the paper.

II. PROBLEM DEFINITION AND ASSUMPTIONS

A distribution grid under the supervision of a DSO is considered. There are different types of customers in this grid, and their loads can be classified into controllable and uncontrollable loads. Controllable loads are assumed to be equipped with customer management units (CMUs). CMUs receive different information including price, weather, and device parameters from data providers and measurement devices, run optimization problems, and generate optimal control signals for devices. End-users are assumed to be in contract with an aggregator, meaning each controllable device belonging to the same end-user can receive the external signals sent by the aggregator from the local CMU. The assumption is that there are several aggregators offering services in the same area and customers can choose among them regardless of their location in the grid.

The interaction between the aggregator and controllable device is similar to the PEM approach introduced in [11], i.e., at the device level, the CMU decides on sending or not sending a GAR or opting out from the program and applies a desirable control to the load. The GAR or opt-out request is sent to the aggregator. The aggregator collects all the requests received during the specific time intervals, considers its commitments to DSO and TSO, accepts all opt-out requests, decides on accepting or rejecting the GARs, and sends back the results to CMU. Finally, the received responses are applied to the devices. There are two main differences between the proposed method in this paper and the PEM. First, this paper uses optimization methods to generate GAR or opt-out signal which leads to an optimal decision, while PEM uses a lightweight algorithm which leads to suboptimal solutions. Second, the focus in the PEM is on the interaction between one aggregator and controllable loads, while in this paper, we consider several aggregators and define a framework for coordinating the operation between each aggregator and its contracted devices and among all aggregators.

As mentioned earlier in Section I, the interaction between each aggregator and devices is similar to the PEM approach. We suggest that the interaction between the aggregators and the DSO should also be defined similarly to the PEM approach, i.e., the aggregators send their aggregated GAR and opt-out powers to the DSO, the DSO collects, accept all opt-out requests, decides on accepting or rejecting the requests considering the grid status, and sends back the results to the aggregators. This gives a two-stage coordination mechanism in which at each stage a PEM approach is executed to manage the loads.

The interaction between aggregators and DSO can be for providing different services. In this work, our focus is on coordinating the loads for preventing the transformers' overloads. It is assumed that there are different transformers in the grid and the grid after each transformer node is radial. The contracted devices of each aggregator can be supplied by different transformers and the aggregator should consider this fact in its decision-making. Furthermore, it is assumed that each aggregator has commitments in the day-ahead market for consuming electricity by its contracted devices which should try not to violate these commitments.

Different controllable devices can be considered for the study. Heat pumps (HP) and hybrid PV/battery setups are two of the most popular controllable devices in Denmark. Our focus is on customers with swimming pool heating systems (SPHSs) supplied by HPs and PV/battery setups as controllable devices at the customer level. However, the method can be applied to any controllable device.

III. PROPOSED FRAMEWORK

Fig. 1 presents the block diagram of the proposed framework. Devices, lines, and blocks presented in blue and green are related to arbitrary aggregators *m* and *n*, respectively. The sequence of actions is explained in the following subsections.

A. Decision Making in the Customer Level

In the first step, the CMU of each device should decide on sending or not sending GAR or opting out of the program temporarily. To this end, an optimization problem should be formulated and solved for each household that includes controllable devices. The goal of this optimization problem is to minimize the electricity cost considering the prices received from TSO and operational constraints. The schematic representation of the PV/battery setup is illustrated in Fig. 2. An optimization problem for this setup has already been formulated in [12] as a mixed integer linear programming (MILP) approach and is used in this paper. Fig. 3 illustrates the schematic of a SPHS. The problem of optimal scheduling of the SPHSs is also investigated in [13] in detail as a MILP problem and used to obtain optimal operation of HPs. Now, each device decides on its next action using the proposed Algorithm ***A***. It can be seen that opt-out happens when keeping the device OFF leads to an

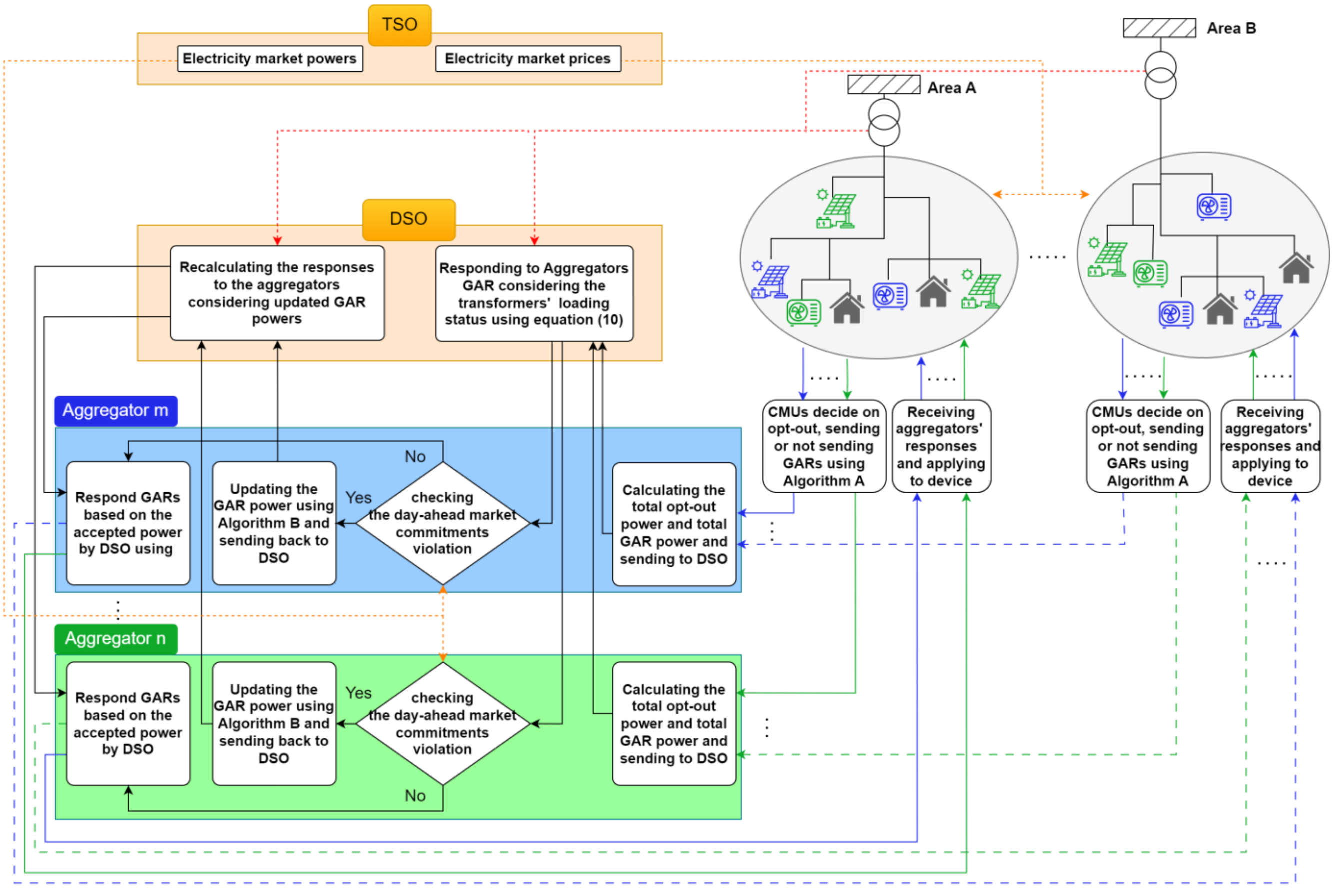


Fig. 1. Framework of the proposed two-stage coordination mechanism.

infeasible solution, i.e., violating the operational and QoS constraints.

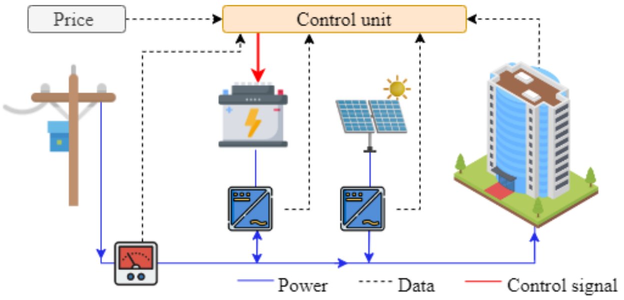


Fig. 2. Schematic representation of PV/Battery setup.

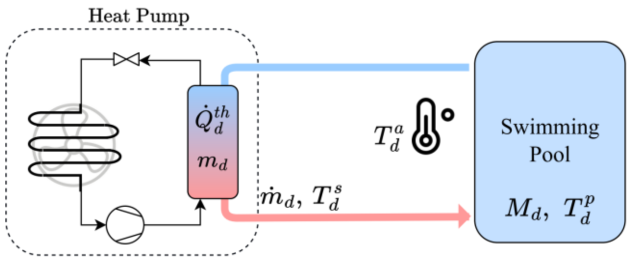


Fig. 3. Schematic representation of SPHS.

Algorithm *A*: Decision making process in the customer level

```
1. Set the decision variable (HP ON/OFF status variable
   and battery charging and discharging variables) equal
   to zero for the next time interval.
2. Run the optimization problem for the controllable
   device
3. If the soultion status is infeasible:
     • Opt out from the program
     • Assign the maximum value for the state variable for
       next time interval and send it with opt-out request
       ($p_{j,t}^{Opt}$).
   Else:
     • Run the optimization problem without fixing the
       state variables.
       If the value of decision variables is zero:
         • Don't send a GAR
       Else:
         • Send a GAR and the requested power ($p_{j,t}^{GAR}$)
```

B. *Aggregating the GAR and Opt-out Requests*

In time interval t, total GAR and opt-out power of devices located at area a that are in contract with aggregator i are obtained as below:

$$P_{i,a,t}^{GAR} = \sum_{j\in D_{i,a,t}} p_{j,t}^{GAR} \qquad \forall\, i \in C, a \in A, t \in T \tag{1}$$

$$P^{Opt}_{i,a,t} = \sum_{j \in D_{i,a,t}} p^{Opt}_{j,t} \qquad \forall\, i \in C, a \in A, t \in T \tag{2}$$

where C, A, and T are the sets of aggregators, areas, and time intervals, respectively. $D_{i,a}$ is the set of devices in the area a in contract with aggregator i that send a request in time interval t. The aggregator sends these requests to the DSO.

C. *DSO Response to Aggregators' Requests (First Round)*

DSO receives the loading status of the transformer of the area a in time interval t from metering devices ($P^{TR}_{a,t}$) and considering the nominal active power of each transformer ($P^{TR,n}_{a}$) determines the remained capacity for loading each transformer ($P^{R}_{a,t}$) as below:

$$P^{R}_{a,t} = P^{TR,n}_{a} - P^{TR}_{a,t} \qquad \forall\, a \in A, t \in T \tag{3}$$

The DSO accepts all opt-out requests. Then, the value of GAR power accepted for each aggregator ($P^{Acc}_{i,a,t}$) is calculated using Algorithm ***B***. Based on algorithm ***B***, the DSO accepts all negative aggregated GARs (Discharge requests for batteries), adds them to the remained capacity of the transformer, and shares the updated remaining capacity among aggregators. C_a and C^n_a are the set of aggregators in area a and the set of aggregators with negative GAR in area a.

D. *Checking the Aggregators' Commitments in the Day-ahead Market*

As mentioned in Section II, each aggregator can commit to the electricity market for electricity consumption. In the designed mechanism, the aggregator i should manage the GARs such that the total consumption does not get greater than the scheduled power in the electricity market ($P^{EM}_{i,t}$) at each time interval t. Algorithm ***C*** is used to manage the total accepted GARs for this purpose. According to algorithm ***C***, first, the power consumption of opt-out devices and the devices that are already ON and will be ON in the next time interval are deducted from $P^{EM}_{i,t}$ to obtain the remaining scheduled power in the electricity market ($P^{EM,R}_{i,t}$). Then, if the total accepted GARs is greater than $P^{EM,R}_{i,t}$, the total GAR power is modified and sent to DSO again.

Algorithm *B*: DSO response to aggregators request

```
1. $P^{R,F}_{a,t} = P^{R}_{a,t} - \sum_{i \in C_a} P^{Opt}_{i,a,t}$
2. For $i$ in $C^n_a$
       $P^{Acc}_{i,a,t} = P^{GAR}_{i,a,t}$
       $P^{R,F}_{a,t} = P^{R,F}_{a,t} - P^{GAR}_{i,a,t}$
3. If $P^{R,F}_{a,t} > 0$
       For $i$ in $C_a - C^n_a$
           If $\sum_{j \in C_a - C^n_a} P^{GAR}_{j,a,t} \ge P^{R,F}_{a,t}$
               $P^{Acc}_{i,a,t} = P^{R,F}_{a,t} \times \frac{P^{GAR}_{i,a,t}}{\sum_{j \in C_a - C^n_a} P^{GAR}_{j,a,t}}$
           Else
               $P^{Acc}_{i,a,t} = P^{GAR}_{i,a,t}$
4. If $P^{R,F}_{a,t} \le 0$
       For $i$ in $C_a - C^n_a$
           $P^{Acc}_{i,a,t} = 0$
```

Algorithm *C*: Checking aggregators commitments in electricity market

```
1. $P^{EM,R}_{i,t} = P^{EM}_{i,t} - \sum_{a \in A_i} P^{Opt}_{i,a,t} - \sum_{a \in A_i} P^{Cons}_{i,a,t+1}$
2. For $i$ in $A^n_i$
       $P^{GAR,M}_{i,a,t} = P^{Acc}_{i,a,t}$
       $P^{EM,R}_{i,t} = P^{EM,R}_{i,t} - P^{Acc}_{i,a,t}$
3. If $P^{R,F}_{a,t} > 0$
       For $a$ in $A_i - A^n_i$
           If $\sum_{k \in A_i - A^n_i} P^{GAR}_{i,k,t} \ge P^{EM,R}_{i,t}$
               $P^{GAR,M}_{i,a,t} = P^{EM,R}_{i,t} \times \frac{P^{Acc}_{i,a,t}}{\sum_{j \in A_i - A^n_i} P^{Acc}_{i,a,t}}$
           Else
               $P^{GAR,M}_{i,a,t} = P^{Acc}_{i,a,t}$
4. If $P^{EM,R}_{i,t} \le 0$
       For $i$ in $A_i - A^n_i$
           $P^{GAR,M}_{i,a,t} = 0$
```

E. *DSO Response to Aggregators' Requests (Second Round)*

If the total GARs power of an aggregator changes, the DSO should recalculate the responses to aggregators. Similar to the first round, Algorithm ***B*** is used to update the responses.

F. *Disaggregating the Accepted Total GAR Power*

After finalizing the total accepted power for each area, the aggregator should disaggregate these powers among the controllable devices that have already sent GARs. To this end, first, all the GARs with negative values are accepted. Then the GARs with positive values are chosen randomly until the total accepted GARs power is covered. The results are sent back to CMUs and applied to devices.

Remark: It is worth mentioning that PEM works based on asynchronous GARs. This means that CMUs do not send the GARs and opt-out requests at the same time. So, each aggregator considers time intervals for collecting all these requests, and then aggregating them and sending them to the DSO. Similarly, the DSO receives the requests from aggregators in specific time intervals and then responds to them altogether.

IV. CASE STUDY

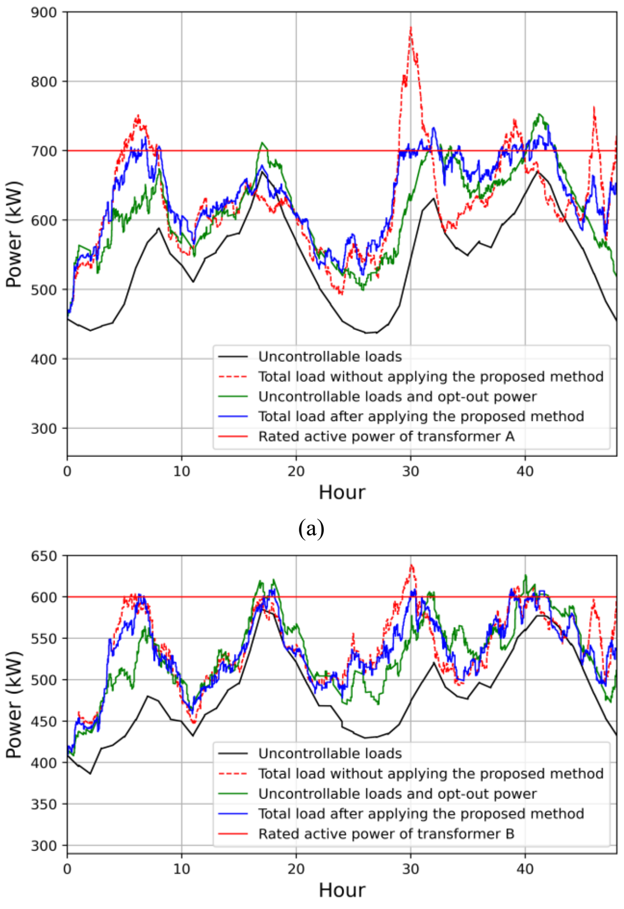
A distribution grid under the supervision of a DSO is considered. Two specific areas A and B with radial grids that are supplied through transformers T^A and T^B. The active rated power of T^A and T^B are assumed to be 700 kW and 600 kW, respectively. Two aggregators AG^1 and AG^2 are considered. The number of SPHSs and PV/battery setups under the contract of each aggregator at each area is presented in Table I. Parameters of SPHSs and PV/battery setups are chosen in reasonable ranges obtained from the literature [12][13]. Uncontrollable loads are modeled as one aggregated load for each area and their volumes are determined by scaling the day-ahead market power consumption in two consecutive days in September 2022. Day-ahead market prices for these two days plus a constant term representing the taxes and tariffs are taken into account as electricity prices for this study.

TABLE I. NUMBER OF SPHSS AND PV/BATTERY SETUPS MANAGED BY EACH AGGREGATOR AT EACH AREA

	Area A		Area B	
	SPHS	PV/battery	SPHS	PV/battery
Aggregator 1	20	15	30	10
Aggregator 2	20	30	10	20

A. *Evaluating the Performance of the Method in Preventing the Transformers Overload*

The total loading of transformers T^A and T^B with and without implementing the proposed method are compared in Fig. 4. It can be seen that when transformers' loading is not controlled, i.e., all the requests are accepted, T^A and T^B can get overloaded up to 27% and 7.5%. Using the proposed coordination method, the maximum loading of transformers decreases significantly, and the maximum violation of the rated active powers is less than 3%. As highlighted in green color in Fig. 4, these minor violations of limits are due to the opt-out of some of the devices that are always accepted by aggregators and the DSO to ensure QoS for the customers and sudden changes in uncontrollable loads such as PV units. It is also worth mentioning the positive role of batteries in reducing the peak demand during peak hours. While opt-out of some of the SPHSs in hour 18:00 overload transformers, discharging the batteries reduces the peak demand to less than the transformers' rated power.



(a)

(b)

Fig. 4. Comparing the transformer loading with and without applying the proposed method for a) area A and b) area B.

B. *Evaluating the Performance of the Method in Responding to Aggregators' Commitments in the Electricity Market*

The total scheduled power of the aggregators and the realized values are presented in Fig. 5. It can be seen that aggregators' commitments are satisfied in the most time intervals. Similar to section IV.A, minor violations from the commitments are due to the opt-out requests of the devices that are always accepted at any circumstances.

In practice, market players should try to follow their scheduled power in the electricity markets as a reference set point and avoid both over-consumption and under-consumption compared to the scheduled power. However, the PEM method is designed to reduce the power consumption of the aggregated load. So, the proposed method can be used to prevent only from over-consumption of power and other methods should be used to cover the under-consumption issue er which is beyond the scope of this paper.

C. *Impacts of the Proposed Method on Devices Operation*

Accepting and rejecting the requests can affect the operation of devices. To illustrate this fact, the operation of a battery and the variation of the temperature of a pool with and without considering the proposed coordination method are compared in Fig. 6. As shown in Fig. 6(a) rejecting the GAR of a battery at hour 10:00 results in not fully charging the battery and reducing the efficiency of using batteries.

Regarding the swimming pool, the water temperature should be inside the upper and lower bounds defined by the end user. As shown in Fig. 6(b), the water temperature is still inside the defined range however its variation has changed because of the changes in the ON/OFF status of the HP due to rejecting the GARs in some time intervals.

D. *Cost-benefit Analysis of the Proposed Method*

In this section, the impacts of the proposed method on the electricity cost of the customers that are in contract with aggregators are evaluated. Table 2 presents the simulation results for the three following cases:

- **Case 1**: Ignoring both roles of the aggregator, i.e., commitments in the electricity market and satisfying transformers limitations and accepting all GARs;
- **Case 2:** Taking into account only the role of aggregators in preventing transformers overloading;
- **Case 3**: Taking into account both roles of aggregators.

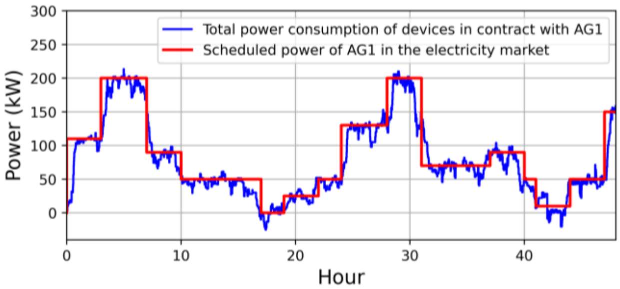
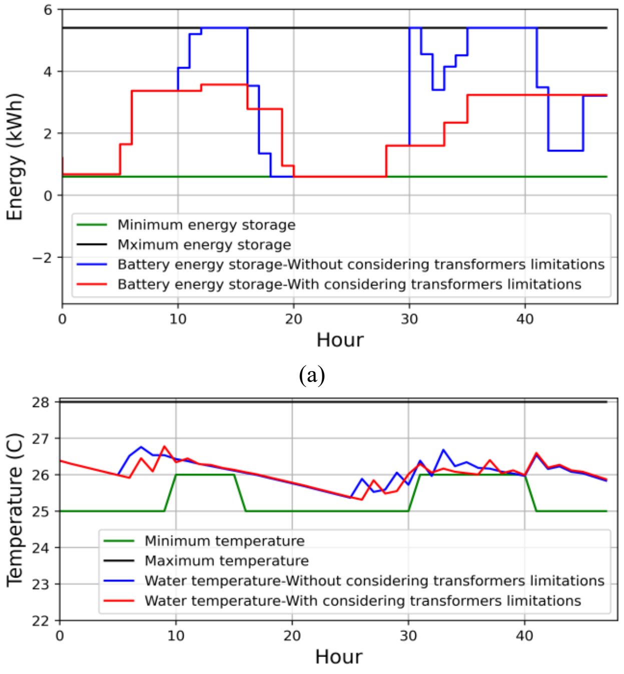


Fig. 5. Comparing the scheduled powers and realized powers for aggregator AG1.



(a)

(b)

Fig. 6. Comparing the operation of a) battery, b) SPHS with and without applying the coordination method

TABLE II. TOTAL COST OF CUSTOMERS WITH SPHSS AND PV/BATTERY SETUPS IN DIFFERENT CASES.

	Case 1	**Case 2**	**Case 3**
Total electricity cost ($)	5029	5160	5264

Considering case 1 as the base case, it can be seen that for the studied case, the electricity cost of consumers increases by about 2.6% when the aggregator provides grid service for DSO (case 2). Taking into account both roles of the aggregator (case 3) leads to 4.6% increase in the total electricity cost of customers. Although this cost may not be noticeable in the electricity bills, the DSO should cover it for customers.

V. CONCLUSION

In this paper, a new load coordination mechanism was introduced. The proposed method extends the proposed PEM approach in the literature such that 1) the sub-optimal PEM algorithm at the customer level is replaced by optimal decision-making strategies for deciding on sending or not sending GARs or opt-out, 2) the possibility of covering the grid by more than one aggregator and the coordination between different aggregators is addressed by introducing a new two-stage coordination mechanism.

In the studied case, reducing the loading of the distribution grid transformers and preventing their overloading is chosen as the objective of the DSO in interactions with aggregators. Furthermore, aggregators' commitments in the electricity market are also included in the model.

Simulation results show that using the proposed coordination mechanism, the loading of transformers can decrease up to 27% and the transformer's rated power violation reduces to 2%. These minor violations are mostly due to the opt-out possibility defined for devices. Simulation results also highlight the effectiveness of the method in following the electricity market commitments by aggregators. Calculations of the studied case show that applying the proposed coordination mechanism increases the total cost of customers by 4.6% which is not significant but should be covered by DSO.

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