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Two-Tier Demand Response with Flexible Demand Swap and Transactive Control for Real-Time Congestion Management in Distribution Networks

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Abstract- With increasing deployment of distributed energy resources, network congestion is becoming a major concern of distribution system operators for secure operation of distribution networks. Real-time congestion management is important as congestion may occur at real-time operation due to forecast errors and components failures. To alleviate real-time congestion within distribution networks, demand response based congestion management schemes have been proposed. However, customers' requirements on energy rebound, i.e., periods and amounts of energy rebound, are not considered in the existing demand response based congestion management schemes. Moreover, customers' willingness to provide flexibilities for congestion management is not taken into account either. To resolve these issues, this paper proposes a two-tier demand response scheme with flexible demand swap and transactive control for real-time congestion management in distribution networks. With flexible demand swap and swap market, real-time congestion can be efficiently solved. Customers are able to rebound energy in multiple periods and determine the amounts of energy rebound by themselves. The proposed transactive control based interactive mechanism between aggregators and customers considers customers' willingness to provide flexibilities. The Roy Billinton Test System (RBTS) was used to conduct case studies to validate the proposed two-tier demand response scheme for real-time congestion in distribution networks. The case study results demonstrate that the proposed two-tier demand response scheme can resolve congestion efficiently while considering customers' requirements on energy rebound and willingness to provide flexibilities for congestion management.

Keywords: Congestion management, demand response, distribution networks, flexible demand swap, transactive control.

Nomenclature

Sets:

N_d	Set of load points in the distribution network
N_s	Set of available swaps
N_s^*	Set of selected swaps

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N_c	Set of customers who participate in the transactive markets
N_T	Set of planning periods in the DR scheme
L	Set of congested lines
D	Set of sides of a swap, d_1 represents $\mathrm{S}^{(1)}$, d_2 represents $\mathrm{S}^{(2)}$
$C_{s,d,t}$	Set of customers belonging to d-th side of s-th swap in period t.
$N_{\mathrm{d}}^{(1)}, N_{\mathrm{d}}^{(2)}$	Set of load points of $\mathrm{S}^{(1)}$ and set of load points of $\mathrm{S}^{(2)}$

Parameters:

$p_{t_1}^{\mathrm{d}}$	The amount of a power consumption reduction at the congested hour t_1 in each swap
$\delta_{i,t}^{\max}$	The allowable maximum modification of the power consumption target of i-th customer in period t
f_l	l-th congested line's loading value exceeding the limit
f^{r}	The remaining capacity of uncongested lines
T	Power transfer distribution factor (PTDF) matrix
V_0	Voltage at the substation node
$V^{\min}$	The lower limit of voltage
$q_{j^*}^{\mathrm{c}}$	Conventional reactive demand at node j^*
$p_{j^*}^{\mathrm{c}}$	Conventional active demand at node j^*
$K_{i,t}^{\mathrm{des}}$	The desired household temperature of i-th customer in period t
K_{i,t_0}	The initial household temperature of i-th customer one hour before providing flexibilities
$A_{i,t}$	The power to temperature matrix of i-th customer in period t.
$b_{i,s,d,t}$	Mapping matrix. $b_{i,s,d,t} = 1$ if customer i belongs to the d-th side of s-th swap in period t; otherwise, $b_{i,s,d,t} = 0$
$p_{i,t}^{\mathrm{da}}$	The day-ahead scheduled power consumption of i-th customer in period t
$p_{s,t}^{\mathrm{r,max}}$	The maximum allowable amount of energy rebound of s-th swap in period t
c	The profit coefficient of the aggregator
$\lambda^{\max}$	The upper limit of the clearing price
$\theta_{i,t}$	The inverse of the response curve's slope of i-th customer in period t
t_1	t_1 is the time period in which a power consumption reduction is required.

Variables:

$p_{s,t}^{\mathrm{r}}$	The amount of energy rebound in period t in s-th swap
$\delta_{i,t}$	The modification of the power consumption target of i-th customer in period t
$\lambda_{s,d,t}^{\mathrm{cl}}$	The clearing price for d-th side of s-th swap in period t
$p_{i,t}^{\mathrm{tar}}$	The power consumption target of i-th customer in period t
$p_{i,t}^{\mathrm{a}}$	The actual power consumption of i-th customer in period t.
$R_{i,t}$	Received reimbursement of i-th customer in period t
$x_{s,j}$	Binary variable representing whether the j-th load point in s-th swap is selected
$y_{s,j}$	Binary variable representing whether the j-th load point in s-th swap is selected
$r_{s,d,t}$	The total difference between the actual and day-ahead scheduled power consumption of those customers who belong to d-th side of s-th swap in period t.
$z_{i,t}^1, z_{i,t}^2$	Binary variables indicating the direction of power consumption modification of i-th customer in period t
$z_{i,t}$	Binary variable indicating whether the power consumption modification reaches the maximum allowable value
Cost_s	The total paid reimbursement of s-th swap
Pr_s	The price of s-th swap bid.

t_2	t_2 is the time period in which the energy rebound occurs
$p^{\mathrm{r}}_{t_2}$	The amount of the energy rebound in time period t_2

1. Introduction

Energy strategy 2050 is a huge step towards realizing the Danish government's vision of independence of fossil fuels [1]. Such an ambitious vision induces increasing deployment of renewable energy resources (RESs), such as wind power (WP) and solar power (SP), and distributed energy resources (DERs) in power systems. Large-scale integration of DERs, such as electrical vehicles (EVs) and heat pumps (HPs), will challenge power system operation, especially for distribution networks [2]. Network congestion limits power transfer from one location to another in the network and hinders integration of DERs [3]. Therefore, congestion management is becoming one of critical tasks of distribution system operators (DSOs) for secure operation of distribution networks and achieve optimal use of energy resources.

Demand response (DR) is defined as a program established to motivate changes in electricity consumption of end-users in response to changes of electricity prices overtime or given incentives [4]. With the advent of smart grids, DR plays an active role in improving grid efficiency [5] and reliability, such as frequency regulation [6] and voltage control [7], and assists in utilizing DERs [8]. In addition to direct congestion management strategies, such as grid reinforcement [9] and network reconfiguration [10], the applications of DR to congestion management for distribution networks have received considerable attention.

1.1. Review of demand response based congestion management schemes for distribution networks

A large number of DR based congestion management schemes have been proposed for the day-ahead and real-time congestion management of distribution networks. The existing DR schemes can be categorized into two types, namely price-based and incentive-based DR schemes [4]. Price-based DR schemes refer to changes in electricity consumption of customers in response to changes in electricity prices. Incentive-based DR schemes give customers load reduction incentives that are separate from, or additional to, electricity prices to motivate customers to change their power consumption patterns.

1.1.1. Day-ahead congestion management

For day-ahead congestion management of distribution networks, the price-based DR schemes include the dynamic tariff (DT) method [11-15], dynamic power tariff method [16], dynamic subsidy method [17] and shadow price method [18]. All these methods have a common feature that the final electricity prices in congested hours are higher than those in hours without congestion. Aggregators, as profit-seeking utilities, shift flexible demands to uncongested hours to minimize their energy costs and, in turn, the congestion is resolved. In the DT method, congestion management is implemented in a decentralized manner. The DSO calculates and sends DTs to aggregators and aggregators independently make their energy plans based on base electricity prices and DTs. The study in [11] developed a DT model maximizing the social surplus to obtain DTs and coordinate EV charging for congestion management. Although the DT models in [11] are effective in most cases, aggregators' optimizations might have multiple solutions because of the linear formulation of the DT model, which results in a failure of the de-centralized congestion management method. To resolve this issue, a quadratic programming (QP) formulation was developed in [12] to ensure the equivalence of the optimal solutions obtained with the DSO optimization and aggregators' optimizations. In all the above-mentioned DT methods, it is assumed that the DSO can accurately predict energy requirements of flexible demands, based on which a centralized optimization is conducted by the DSO to calculate DTs. However, uncertainties of flexible demands significantly influence the effectiveness of the DT method. Therefore, an uncertainty management scheme for the DT method was developed in [13], in which a certain margin of the line capacity is reserved to ensure the effectiveness of the deterministic DT model under uncertainties. A distributed optimization based DT model was developed in [14], in which the DSO does not require private information of flexible demands, and DTs are obtained through an iterative mechanism between the DSO and aggregators. A chance constrained mixed-integer program based DT model was developed in [15] which models uncertainties of EV charging behaviors by chance constraints.

Different from the DT method that charges tariffs to customers without considering their power consumption levels, a dynamic power tariff method was proposed in [16] to solve day-ahead congestion that charges tariffs based on the consuming power. In this work, the dynamic power tariffs are obtained using an iterative mechanism which is similar to the one in [14]. With dynamic power tariffs and electricity prices, EV charging and HP power consumption is coordinated to relieve congestion. Instead of collecting tariffs from customers in congested hours, a dynamic subsidy method was proposed in [17] in which the DSO pays subsidies to customers in uncongested hours and consequently leading to higher final prices in congested hours. Based on decomposition techniques, line shadow price methods were proposed in [18] to solve day-ahead congestion. The shadow price method works similarly to the DT method but requires iteration processes to determine final shadow prices. The shadow price concept was proposed in [18] to solve congestion and the dual decomposition technique was used to calculate shadow prices.

For the incentive-based DR schemes for day-head congestion management, a monetary incentive-based DR scheme was proposed in [19], in which customers minimize their energy costs based on electricity prices and additional incentives, and an optimal set of incentives were obtained by iteration processes between aggregators and customers. Another type of incentive-based DR scheme is to establish a DR market, such as the flexibility clearing house (FLECH) and DR exchange platform (DRX). The FLECH is a service-oriented platform that facilitates the trading process of flexibility services from DERs [20]. A decision support tool was developed in [21] to help DSOs buy flexibility services with the minimized procurement cost to relieve congestion. A hierarchy congestion management scheme was proposed in [22] to integrate the Flex-market and network reconfiguration in the tertiary control level. The above-mentioned Flex-market coexists with existing energy markets, such as the spot market, and only DSOs and aggregators participate in the market. A more advanced pool-based market for DR, i.e., the DRX market, was proposed in [23]-[24]. In the DRX market in [23], besides aggregators and DSOs, TSOs also utilize flexibility services to address security issues in transmission networks. In [24], a Walrasian auction based market clearing scheme was developed to realize a decentralized clearing scheme for the DRX market.

A comprehensive congestion management scheme integrating the price-based DR scheme and incentive-based DR scheme was proposed in [25]. In the study, a relaxed DT model is employed to solve congestion with limited DTs in the first step. Then, the flexibility services in the flexibility market are purchased by the DSO to solve the remaining congestion.

1.1.2. Real-time congestion management

As important as day-ahead congestion management, real-time congestion due to forecast errors and unexpected component failures in real-time operation should be addressed as well. Real-time congestion management refers to the congestion management close to real-time operation, i.e., 5-60 minutes prior to operation time [26]. Currently, the applications of DR to deal with real-time congestion at the distribution level are limited. A flexible demand swap based DR scheme was developed in [26] to use flexible demand swap to resolve real-time congestion which can address both the rebound effect and imbalance issue. A coupon incentive-based DR (CIDR) scheme was developed in [27] to handle real-time congestion. In contrast to the real-time pricing scheme, the CIDR scheme provides customers with flat rates and offers coupon incentives to motivate customers to reschedule real-time power consumption. An agent-based integrated real-time congestion management scheme was introduced in [28], in which DERs are represented by agents and send flexibility bids to the DSO, and then the DSO selects flexibility bids with the minimized cost to relieve congestion. Moreover, active power curtailment is considered as a backup option in the study for real-time congestion management.

1.2. Motivations

There are two important aspects to be taken into account in the applications of DR for real-time congestion management. The first aspect is to satisfy customer's requirements on energy rebound, i.e., the periods and amounts (rebound percentage) of energy rebound. If specific requirements on the rebound percentages cannot be met, certain constraints of customers will be violated, e.g., an energy rebound of 100% (rebound percentage of 100%) for HPs may result in household temperature exceeding the upper limit because the required rebound percentage of HP is lower than 100% [29-30]. The second aspect is to consider customers' willingness to provide flexibilities for congestion management. For example, conservative customers may not be willing to provide flexibilities. To reduce discomfort to customers, customers' willingness to provide flexibilities should be considered.

However, the above-mentioned two aspects have not been considered in the existing DR based real-time congestion management schemes. In [27], the rebound effect was not considered because the intertemporal features of flexible demands are not modelled. The rebound effect was studied in [26, 28], however, requirements on energy rebound percentages and periods are not considered. In [26], an energy rebound of 100% was set to occur in a specified period. In addition, none of them has considered customer' willingness to provide flexibilities. Therefore, to resolve these issues of the existing DR based real-time congestion management schemes, a two-tier DR scheme with flexible demand swap and transactive control is proposed for real-time congestion management. The benefits of the proposed DR scheme are summarized as follows: 1) the proposed DR scheme considers customers' requirements on energy rebound. In the proposed scheme, customers are able to rebound energy in multiple periods and determine the amounts of energy rebound (rebound percentages); 2) the proposed DR scheme considers customers' willingness to provide flexibilities and cause less discomfort to them.

The contributions of this paper are summarized as follows: 1) propose a two-tier DR scheme with the flexible demand swap and transactive control for real-time congestion management of distribution networks; 2) propose a new operation mechanism for the flexible demand swap market which allows customers to determine periods and amounts of energy rebound; 3) develop a transactive control based interactive mechanism between the aggregators and customers, which takes into account customers' willingness to provide flexibilities for real-time congestion management. The rest of the paper is organized as follows. The flexible demand swap and transactive control are described in Section 2. The framework of the proposed DR scheme is presented in Section 3. Section 4 provides the implementation of the proposed DR scheme and algorithm. The case study is presented and discussed in Section 5, followed by conclusions.

2. Flexible demand swap and transctive control

2.1. Concept of the flexible demand swap

The congestion in the distribution network can be resolved by a flexible demand swap without causing the system imbalance and forming new peaks [26]. One side of a swap ($\mathrm{S}^{(1)}$) can be defined as,

$$\mathrm{S}^{(1)}:\left\{\mathrm{LP}_j \,\middle|\, j\in \mathrm{N}_{\mathrm{d}}^{(1)}\right\},\left(t_1,-p_{t_1}^{\mathrm{d}}\right),\left(t_2,+p_{t_2}^{\mathrm{r}}\right) \tag{1}$$

where a set $\{\mathrm{LP}_j | j\in \mathrm{N}_{\mathrm{d}}^{(1)}\}$ represents a joint of load points providing flexibilities; notations "-" and "+" represent the power consumption decrease and increase, respectively; t_1 is the time period (when and how long) in which a power consumption reduction is required; $-p_{t_1}^{\mathrm{d}}$ represents a power consumption reduction with the total amount $p_{t_1}^{\mathrm{d}}$ at the specified load points in period t_1; t_2 is the period in which the energy rebound occurs; $+p_{t_2}^{\mathrm{r}}$ means a power consumption increase with the total amount of $p_{t_2}^{\mathrm{r}}$ in the period t_2 at the specified load points, which allows customers to rebound energy, e.g., restore their household temperatures.

The other side of the swap ($\mathrm{S}^{(2)}$) is defined as,

$$\mathrm{S}^{(2)}:\left\{\mathrm{LP}_j \,\middle|\, j\in \mathrm{N}_{\mathrm{d}}^{(2)}\right\},\left(t_1,+p_{t_1}^{\mathrm{d}}\right),\left(t_2,-p_{t_2}^{\mathrm{r}}\right) \tag{2}$$

This side of the swap represents the opposite flexibility that is used to maintain the system balance. For example, in the period t_1, a consumption increase with the amount $p_{t_1}^{\mathrm{d}}$ is required at load points $\{\mathrm{LP}_j | j \in \mathrm{N}_{\mathrm{d}}^{(2)}\}$ to compensate the consumption reduction at load points $\{\mathrm{LP}_j | j \in \mathrm{N}_{\mathrm{d}}^{(1)}\}$. Likewise, the swap ensures the system balance in the period t_2.

The distribution network from the Roy Billinton Test System (RBTS) [31], as shown in Figure 1, is used to illustrate how the swap can be used to resolve congestion. Line segments of feeder 1 are labelled as L1-L12 and the first line segment of feeder 2 is labelled as L13. Load points are labelled as $\mathrm{LP}_{1\text{-}7}$, $\mathrm{LP}_{11\text{-}16}$, $\mathrm{LP}_{18\text{-}25}$ and $\mathrm{LP}_{32\text{-}38}$. It is assumed that the congestion occurs in L3 (overloading by p^{d}) at time 18:00 and lasts for 1 hour, and that there is enough capacity in L1 and L2 to implement the opposite flexibilities. Moreover, suppose that there is enough capacity in L3 during 19:00-20:00 to perform the energy rebound with the amount of p^{r}. Then, a swap can be formulated as,

$$\begin{cases} \mathrm{S}^{(1)}: \{\mathrm{LP}_{2-5}\}, \left(18:00, 1\mathrm{h}, -p^{\mathrm{d}}\right), \left(19:00, 1\mathrm{h}, +p^{\mathrm{r}}\right) \\ \mathrm{S}^{(2)}: \{\mathrm{LP}_{1}\}, \left(18:00, 1\mathrm{h}, +p^{\mathrm{d}}\right), \left(19:00, 1\mathrm{h}, -p^{\mathrm{r}}\right) \end{cases} \tag{3}$$

It can be seen that the congestion in L3 at 18:00 can be resolved because the power consumption at $\mathrm{LP}_{2\text{-}5}$ is reduced and customers at $\mathrm{LP}_{2\text{-}5}$ can rebound energy at 19:00 without causing new congestion problems. Moreover, the total power consumption of the distribution network in each time period remains unchanged, implying that the system balance is maintained.

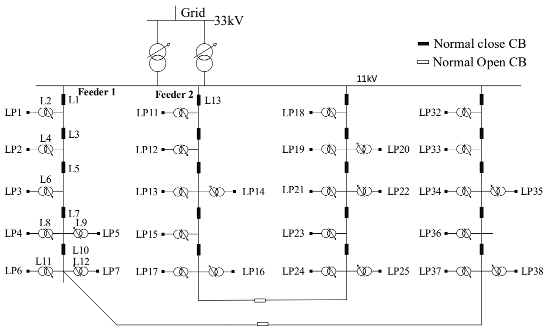

Figure 1. Single line diagram of the distribution network

2.2. Transactive control

Transactive control is a distributed control strategy that uses the market mechanism to engage responsive loads to provide service to grids. Instead of using direct control, transactive control utilizes economic signals as the primary basis for delivering the desire to change operating status of responsive loads [32]. A transactive control based market was proposed in [33] to manage real-time EV charging for providing regulating power in the real-time regulating market.

In the study, based on the transactive control concept, the aggregator constructs a transactive market with customers. In the transactive market, customers submit their power consumption targets and response curves in the specified period, and the aggregator rewards customers for their modifications of power consumption targets. The response curve is illustrated in Figure 2.

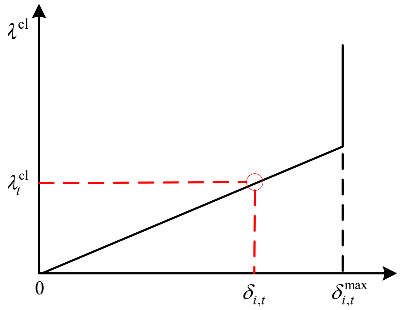

Figure 2. Response curve of a customer

The response curve represents the relation between a customer's power consumption modification ($\delta_{i,t}$) and a unified clearing price (λ_t^{cl}), implying the customer's willingness to change its power consumption target. The coefficient

γ is the slope of the response curve; a smaller γ means a larger power consumption modification with the same price, denoting that the customer is more willing to change its power consumption target.

After receiving the response curves and power consumption targets from customers, the aggregator conducts an optimization to clear the market and broadcasts the clearing price to customers. With the clearing price and response curve, each customer determines its own power consumption modification using (4).

$$\delta_{i,t} = \begin{cases} \theta_{i,t}\lambda_t^{\mathrm{cl}}, \ \lambda_t^{\mathrm{cl}} \le \delta_{i,t}^{\max} / \theta_{i,t} \\ \delta_{i,t}^{\max}, \ \lambda_t^{\mathrm{cl}} > \delta_{i,t}^{\max} / \theta_{i,t} \end{cases} \tag{4}$$

where $\theta_{i,t}$ is the inverse of the response curve's slope. Accordingly, the actual power consumption of each customer in the period is equal to the power consumption target plus or minus the power consumption modification as below.

$$p_{i,t}^{\mathrm{a}} = p_{i,t}^{\mathrm{tar}} + (z_{i,t}^{1} - z_{i,t}^{2})\delta_{i,t}, \ \forall i \in N_c, t \in N_T \tag{5}$$

where $p_{i,t}^{\mathrm{tar}}$ is the power consumption target of i-th customer in period t; $p_{i,t}^{\mathrm{a}}$ is the actual power consumption of i-th customer in period t; $z_{i,t}^{1}$ and $z_{i,t}^{2}$ are binary variables representing the direction of the power consumption modification. The customer's actual power consumption is lower than its power consumption target if $z_{i,t}^{1} = 0$ and $z_{i,t}^{2} = 1$. With the clearing price, the received reimbursement ($R_{i,t}$) of each customer can be determined by,

$$R_{i,t} = \lambda_t^{\mathrm{cl}}\delta_{i,t} \tag{6}$$

It can been seen that the transactive market concept allows customers to change their willingness on the modification of the power consumption target in each period. If a customer wants to be more conservative to provide flexibilities, the customer can increase its response curve' slope. Consequently, the modification of the power consumption target and received reimbursement are reduced.

Take the $\mathrm{S}^{(1)}$ in (3) as an example, in order to resolve the congestion in L3 at 18:00, a power consumption reduction with the total amount of p^{d} is required. It is assumed that customers located at load points LP_2 are willing to participate in the transactive market. Firstly, the aggregator constructs a transactive market with its contractual customers, and customers located at LP_2 submit their response curves and power consumption targets of time 18:00 to the market. Then, the aggregator clears the market in order to have a power consumption reduction with the amount of p^{d} and informs customers about the clearing price. Based on the clearing price and response curves, customers determine their actual power consumption. As a result, the congestion in L3 is resolved.

3. Framework of the two-tier demand response scheme

To consider customers' requirements on energy rebound when implementing DR for congestion management, a new market operation mechanism is developed for the flexible demand swap market. With the new market operation mechanism, aggregators determine swap bids considering customers' requirements and the DSO selects swaps with the minimized procurement cost. It is different from the swap market in [26] where customer's requirements are not taken into account since the DSO determines swaps directly. Moreover, transactive control is used to develop an interactive mechanism between aggregators and customers in order to consider customer's willingness to provide flexibilities for congestion management. With the flexible demand swap, swap market and transactive control, a two-tier DR scheme is proposed for real-time congestion management. The structure of the proposed two-tier DR scheme is shown in Figure 3.

In the upper tier, a swap market is constructed between the DSO and aggregators. Firstly, according to the congestion information, the DSO publishes the requirements on swaps (flexibility tables) to the swap market. Secondly, the aggregators respond to the flexibility tables (FTs) by submitting swap bids to the swap market. Thirdly, the DSO evaluates all the submitted swap bids and chooses the best swap bids. In the lower tier, a transactive market is constructed between the aggregator and customers. After receiving FTs, the aggregator constructs a transactive market with its contractual customers, in which an interactive process is performed to determine the swap bids.

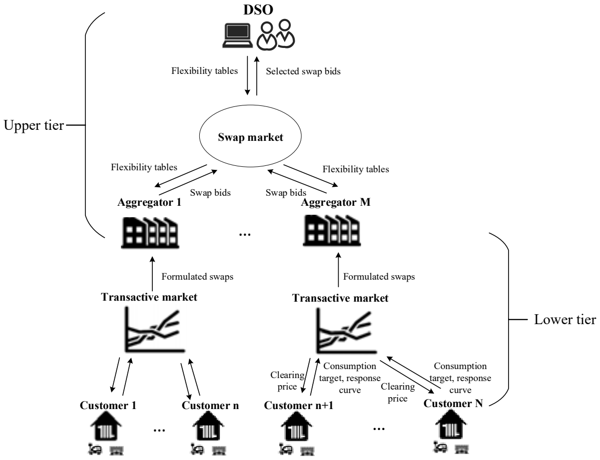

Figure 3. Structure of the proposed two-tier DR scheme

The procedures of using the proposed two-tier DR scheme to resolve real-time congestion are illustrated in Figure 4 and has the following five steps:

1) Prepare FTs. The DSO identifies the congestion of the network 15 minutes in advance so that there is enough time to set up markets (swap market and transactive markets). Then, the DSO formulates FTs according to the congestion information.

2) Publish FTs. The DSO constructs a swap market and publishes the formulated FTs to the market.

3) Aggregators respond. In order to respond to FTs, each aggregator constructs a transactive market with its contractual customers and determines swap bids through an interactive process. Then, aggregators close transactive markets and submit their swap bids to the swap market.

4) Evaluation and selection. The DSO evaluates all the swap bids and chooses the best swap bids according to requirements. Then, the DSO closes the swap market and informs the aggregators whose swap bids are selected.

5) Implementation and financial settlement of the selected swaps. The aggregators implement the selected swaps at the operation time. After the implementation, the DSO settles the swaps.

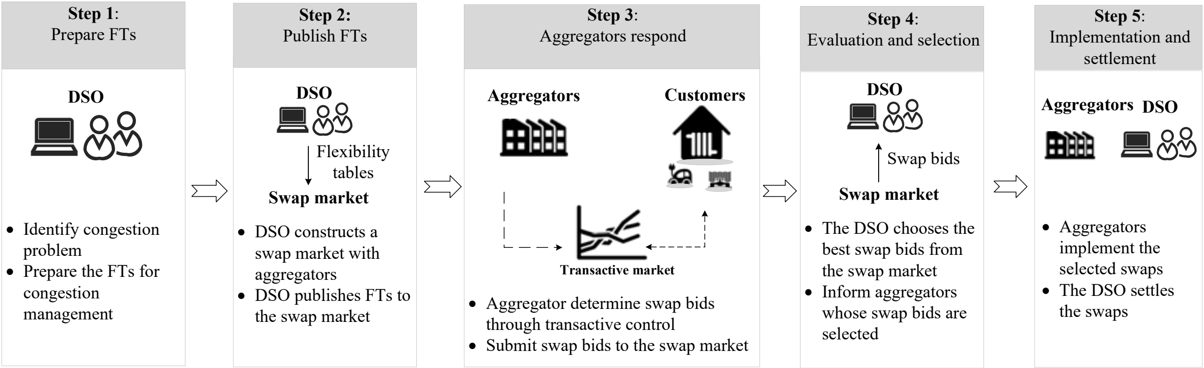

Figure 4. The procedures of using the proposed DR scheme to resolve real-time congestion

3.1. Swap market for the DSO and aggregators

In the proposed bi-level DR scheme, the DSO issues the FTs in the swap market instead of swaps. A FT can be defined as,

$$\begin{cases} \mathrm{S}^{(1)}:\left\{\mathrm{LP}_j \,\middle|\, j\in \mathrm{N}_{\mathrm{d}}^{(1)}\right\},\left(t_1,-p_{t_1}^{\mathrm{d}}\right),\left(t_2,+,\le p_{t_2}^{\mathrm{r,max}}\right),\ldots,\left(t_i,+,\le p_{t_i}^{\mathrm{r,max}}\right) \\ \mathrm{S}^{(2)}:\left\{\mathrm{LP}_j \,\middle|\, j\in \mathrm{N}_{\mathrm{d}}^{(2)}\right\},\left(t_1,+p_{t_1}^{\mathrm{d}}\right),\left(t_2,-,\le p_{t_2}^{\mathrm{r,max}}\right),\ldots,\left(t_i,-,\le p_{t_i}^{\mathrm{r,max}}\right) \end{cases} \tag{7}$$

The FT shows the requirements on swaps for resolving real-time congestion. For example, the FT determines the amount of a power consumption reduction and the amount of a power consumption increase in congested period (t_1) and the candidate load points providing flexibilities. Unlike a swap, the FT determines the maximum allowable amounts of energy rebound ($p_{t_2}^{\mathrm{r,max}}, \ldots, p_{t_i}^{\mathrm{r,max}}$) in multiple periods instead of one fixed amount of energy rebound in one specified period, e.g., $+p_{t_2}^{\mathrm{r}}$ in time period t_2 in (1), which allows the aggregators and customers to make decisions regarding energy rebound. In addition, the FT determines that a power consumption increase must be compensated by a power consumption reduction at the same time, e.g., in period t_2, a power consumption increase ($+p_{t_2}^{\mathrm{r}}$) in $\mathrm{S}^{(1)}$ should be accompanied with a power consumption decrease ($-p_{t_2}^{\mathrm{r}}$) in $\mathrm{S}^{(2)}$.

3.2. Transactive market for the aggregator and its contractual customers

In order to provide swap bids, the aggregator constructs a transactive market with its contractual customers. The interactive process is illustrated in Figure 5.

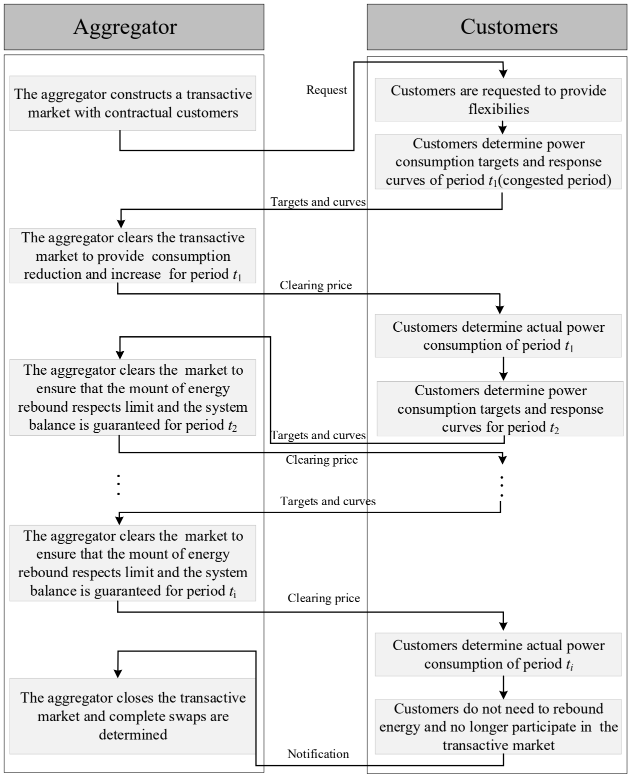

Figure 5. The interactive process between the aggregator and customers

After receiving the FTs, the aggregator constructs a transactive market with its contractual customers. The aggregator first sends the request of providing flexibilities to the customers located at the candidate load points given in the FTs. Each customer can choose to either provide flexibilities for a swap or reject to provide flexibilities. Take the FT in (7) as an example, after customers submit their power consumption targets and response curves of period t_1 to the transactive market, the aggregator clears the market to change customer's power consumption targets to have a power consumption reduction with the amount of $p_{t_1}^{\mathrm{d}}$ for period t_1 in $\mathrm{S}^{(1)}$ and a power consumption increase with the same amount for period t_1 in $\mathrm{S}^{(2)}$. Then, the aggregator broadcasts the clearing price to customers and customers determine their actual power consumption for period t_1. After that, for the following period t_2, customers determine and submit their power consumption targets and response curves to the transactive market. Then, the aggregator clears the market to modify customers' power consumption targets so that the total amount of energy rebound does not exceed the maximum allowable amount ($p_{t_2}^{\mathrm{r,max}}$) given in the FT and the system balance is maintained. Similarly, the market clearing process repeats for the following periods until all customers do not need to rebound energy, i.e., customer's household temperature is restored to a satisfying level. In the interactive process, once a customer does not need to rebound energy, the customer will no longer participate in the transactive market.

Finally, through the interactive process, the amount of energy rebound in each period is determined and a swap is formulated as,

$$\begin{cases} \mathrm{S}^{(1)}:\left\{\mathrm{LP}_j \,\middle|\, j\in \mathrm{N}_\mathrm{d}^{(1)}\right\},\left(t_1,-p_{t_1}^\mathrm{d}\right),\left(t_2,+p_{t_2}^\mathrm{r}\right),\ldots,\left(t_i,+p_{t_i}^\mathrm{r}\right) \\ \mathrm{S}^{(2)}:\left\{\mathrm{LP}_j \,\middle|\, j\in \mathrm{N}_\mathrm{d}^{(2)}\right\},\left(t_1,+p_{t_1}^\mathrm{d}\right),\left(t_2,-p_{t_2}^\mathrm{r}\right),\ldots,\left(t_i,-p_{t_i}^\mathrm{r}\right) \end{cases} \tag{8}$$

In (8), the amount of energy rebound in each period ($p_{t_i}^\mathrm{r}$) is a deterministic parameter respecting the limit given in the FT. Then, the aggregator puts a price tag to each formulated swap according to the reimbursement paid to customers and expected profit for providing the swap. Finally, a complete swap bid is formulated as,

$$\text{Swap bid:}\begin{cases} \text{Price:} \quad \text{price(DKK)} \\ \text{Pattern}:\begin{cases} \mathrm{S}^{(1)}:\left\{\mathrm{LP}_j \,\middle|\, j\in \mathrm{N}_\mathrm{d}^{(1)}\right\},\left(t_1,-p_{t_1}^\mathrm{d}\right),\left(t_2,+p_{t_2}^\mathrm{r}\right),\ldots,\left(t_i,+p_{t_i}^\mathrm{r}\right) \\ \mathrm{S}^{(2)}:\left\{\mathrm{LP}_j \,\middle|\, j\in \mathrm{N}_\mathrm{d}^{(2)}\right\},\left(t_1,+p_{t_1}^\mathrm{d}\right),\left(t_2,-p_{t_2}^\mathrm{r}\right),\ldots,\left(t_i,-p_{t_i}^\mathrm{r}\right) \end{cases} \end{cases} \tag{9}$$

4. Implementation and algorithm of the two-tier demand response scheme

The mathematical formulations of the FTs and swap bid are described in this section. In order to simplify the implementation, the amount of power consumption reduction in period t_1 (congested period) in each swap is standardized to a fixed number p^d, e.g., 100kW, and the duration of each time period is fixed as 1 hour.

4.1. Formulation of the flexibility table

4.1.1. Formulation of $\mathrm{S}^{(1)}$ of the flexibility table

As describe in section 3.1, the $\mathrm{S}^{(1)}$ of a FT should determine the candidate load points that can provide a power consumption reduction and the maximum allowable amount of energy rebound in each period. All candidate load points can be found using the following mixed integer linear programming (MILP) model.

Optimization 1 (OPT.1)

$$\min \sum_{s\in N_s, j\in N_d} x_{s,j} \tag{10}$$

s.t.

$$\sum_{s\in N_s, j\in N_d} p^\mathrm{d} T_{l,j} x_{s,j} \ge f_l,\ \forall l\in L \tag{11}$$

$$\sum_{j\in N_d} x_{s,j} \le 1,\ \forall s\in N_s \tag{12}$$

$$x_{s,j}\in\{0,1\},\ \forall s\in N_s, j\in N_d \tag{13}$$

where N_d is the set of load points; N_s is the set of available swaps; L is the set of congested lines; l denotes the l-th congested line; f_l is the l-th congested line's loading value exceeding the limit; $x_{s,j}$ is the binary variable representing whether the j-th load point in the s-th swap is selected; $T_{l,j}$ is the cell in l-th row, j-th column of the power transfer distribution factor (PTDF) matrix.

The objective function (10) is to minimize the number of swaps needed for congestion management. For example, if the DSO gives a set $N_s = \{s_1, s_2, s_3, ..., s_{10}\}$, but the obtained objective value is 2, which means that only two swaps, e.g., S_1 and S_2, are needed to resolve congestion. Constraint (11) ensures that congestion in each congested line is resolved. Constraint (12) means that each swap includes one load point at the most. Constraint (13) defines the binary nature of the variable $x_{s,j}$. After solving the above model (OPT.1), the minimum number of needed swaps, e.g., S_1 and S_2, and one set of candidate load pints for providing flexibilities are determined as,

$$\begin{cases} \mathrm{S}_1^{(1)}=\left\{\mathrm{LP}_{j_1},t_1,-p^\mathrm{d}\right\} \\ \mathrm{S}_2^{(1)}=\left\{\mathrm{LP}_{j_2},t_1,-p^\mathrm{d}\right\} \end{cases} \tag{14}$$

After obtaining the above solution, add a new constraint to the model to exclude the obtained solution. The new constraint is $x_{s^{'},j_1} + x_{s^{''},j_2} \leq 1$, which means that the already obtained set of load points (LP_{j_1} , LP_{j_2}) cannot occur in the new solution. Then, solve the above model again and a new solution can be found. Repeat this process until no solution can be found or the objective value increases or the total number of solutions reaches a predefined number. Finally, all the candidate load points can be found and grouped in the following form,

$$\begin{cases} \mathrm{S}_1^{(1)} = \left\{ \mathrm{LP}_{j_1}, \mathrm{LP}_{j_3}, ..., \mathrm{LP}_{j_{n1}}, t_1, -p^{\mathrm{d}} \right\} \\ \mathrm{S}_2^{(1)} = \left\{ \mathrm{LP}_{j_2}, \mathrm{LP}_{j4}, ..., \mathrm{LP}_{j_{n2}}, t_1, -p^{\mathrm{d}} \right\} \end{cases} \tag{15}$$

Then, the DSO assigns the maximum allowable amount of energy rebound to $\mathrm{S}_1{}^{(1)}$ and $\mathrm{S}_2{}^{(1)}$. The DSO forecasts the remaining capacity of those critical lines associated with energy rebound and allocates the remaining capacity to each swap. For example, if the obtained two swaps (S_1 and S_2) are used to resolve the congestion in the same line, the remaining capacity of the line in each period is equally divided and allocated to each swap; otherwise, the remaining capacity of two lines is assigned to two swaps accordingly. So far, the $\mathrm{S}_1{}^{(1)}$ and $\mathrm{S}_2{}^{(1)}$ of two FTs are formulated as,

$$\begin{cases} \mathrm{S}_1^{(1)} = \left\{ \mathrm{LP}_{j_1}, \mathrm{LP}_{j_3}, ..., \mathrm{LP}_{j_{n1}}, \left(t_1, -p^{\mathrm{d}}\right), \left(t_2, +, \leq p_{1,t_2}^{\mathrm{r,max}}\right), ..., \left(t_i, +, \leq p_{1,t_i}^{\mathrm{max}}\right) \right\} \\ \mathrm{S}_2^{(1)} = \left\{ \mathrm{LP}_{j_2}, \mathrm{LP}_{j4}, ..., \mathrm{LP}_{j_{n2}}, \left(t_1, -p^{\mathrm{d}}\right), \left(t_2, +, \leq p_{2,t_2}^{\mathrm{r,max}}\right), ..., \left(t_i, +, \leq p_{2,t_i}^{\mathrm{max}}\right) \right\} \end{cases} \tag{16}$$

4.1.2. Formulation of $\mathrm{S}^{(2)}$ of the flexibility table

The objective of $\mathrm{S}^{(2)}$ is to find all candidate load points that can provide opposite flexibilities in period t_1 to guarantee the system balance. According to the number of selected swaps in the formulated $\mathrm{S}^{(1)}$, the following MILP problem (OPT.2) with a dummy objective function is used to generate $\mathrm{S}^{(2)}$.

$$\text{OPT.2} \qquad \min \ 0 \tag{17}$$

s.t.

$$\sum_{s \in N_s^*, j \in N_d} p^{\mathrm{d}} T_j y_{s,j} \leq f^{\mathrm{r}} \tag{18}$$

$$\sum_{j \in N_d} y_{s,j} \leq 1, \ \forall s \in N_s^* \tag{19}$$

$$V_0 \Big(1 - \frac{1}{V_0^2} \sum_{j^{'} \in N_d} \big((p_{j^{'}}^{\mathrm{c}} + p^{\mathrm{d}} \sum_{s \in N_s^*} y_{s,j^{'}}) R_{j,j^{'}} + q_{j^{'}}^{\mathrm{c}} X_{j,j^{'}} \big) \Big) \geq V^{\min}, \ \forall j \in N_d \tag{20}$$

$$y_{s,j} \in \{0,1\}, \ \forall s \in N_s^*, j \in N_d \tag{21}$$

where N_s^* is the set of selected swaps in $\mathrm{S}^{(1)}$; $y_{s,j}$ is the binary variable representing whether the j-th load point in s-th swap is selected; T_j is the j-th column of the PTDF matrix; matrix R and X are real and imagine parts of the inverse matrix of the partial nodal admittance Y_{LL}, which is a submatrix of the admittance matrix Y:

$$Y = \begin{bmatrix} Y_{00} & Y_{0\mathrm{L}} \\ Y_{\mathrm{L}0} & Y_{\mathrm{LL}} \end{bmatrix}$$

Constraint (18) ensures that congestion does not occur after providing the opposite flexibility. Constraint (19) ensures that each swap includes one load point at the most. Constraint (20) calculates voltages according to an approximated method proposed in [34] and ensures that voltages are not violated. Similar to the formulation of $\mathrm{S}^{(1)}$, after repeating solving and updating OPT.2 and excluding the already obtained solution, all candidate load points can be found and the $\mathrm{S}^{(2)}$ of FTs is formed as,

$$\begin{cases} \mathrm{S}_1^{(2)} = \left\{ \mathrm{LP}_j \mid j \in N_{1,\mathrm{d}}^{(2)}, \left(t_1, +p^d\right) \right\} \\ \mathrm{S}_2^{(2)} = \left\{ \mathrm{LP}_j \mid, j \in N_{2,\mathrm{d}}^{(2)}, \left(t_1, +p^d\right) \right\} \end{cases} \tag{22}$$

4.2. Formulation of swap bids

The aggregator interacts with its contractual customers to determine the swap bids according to the FTs. In the study, HPs provide flexibilities to resolve congestion, and it is assumed that if a customer does not participate in the transactive market, the customer implements day-ahead scheduled HP power consumption.

1) Determination of the customer's power consumption target of each period

For each period, each customer determines a power consumption target that can maintain the desired household temperature. The power consumption target of *i*-th customer in period *t* is calculated using the following equation.

$$K_{i,t}^{\mathrm{des}} = K_{i,t_0} + \sum_{t_0 < t^* < t} A_{i,t^*} p_{i,t^*}^{\mathrm{a}} + A_{i,t} p_{i,t}^{\mathrm{tar}}, \ \forall t \in N_T, i \in N_c \tag{23}$$

where $K_{i,t}^{\mathrm{des}}$ is the desired household temperature of *i*-th customer in period *t*, K_{i,t_0} is the initial household temperature of *i*-th customer one hour before providing flexibilities; $A_{i,t}$ is the power to temperature matrix of *i*-th customer in period *t*.

2) Formulations of swaps

After receiving customers' response curves and power consumption targets, each aggregator conducts the following optimization model to clear the transactive market for each period and determines swaps.

The optimization model for period *t* is as follows.

$$\text{OPT.3} \qquad \sum_{s \in N_s^*} \sum_{i \in N_c} \sum_{d \in D} b_{i,s,d,t} \theta_{i,t} \left(\lambda_{s,d,t}^{\mathrm{cl}}\right)^2, \ \forall t \in N_T \tag{24}$$

s.t.

$$\sum_i b_{i,s,d,t} (p_{i,t}^{\mathrm{a}} - p_{i,t}^{\mathrm{da}}) = r_{s,d,t}, \ \forall s \in N_s^*, d \in D, t \in N_T \tag{25}$$

$$r_{s,d,t} = -p^{\mathrm{d}}, \ d = d_1, t = t_1, \forall s \in N_s^* \tag{26}$$

$$r_{s,d,t} \le p_{s,t}^{\mathrm{r,max}}, \ d = d_1, \forall t > t_1, s \in N_s^* \tag{27}$$

$$\sum_d r_{s,d,t} = 0, \ \forall t \ge t_1, s \in N_s^* \tag{28}$$

$$p_{i,t}^{\mathrm{a}} = p_{i,t}^{\mathrm{tar}} + (z_{i,t}^1 - z_{i,t}^2)\delta_{i,t}, \ \forall i \in N_c, t \in N_T \tag{29}$$

$$\delta_{i,t} = \theta_{i,t} \lambda_{s,d,t}^{cl} (1 - z_{i,t}) + \delta_{i,t}^{\max} z_{i,t}, \ \forall i \in C_{s,d,t}, s \in N_s^*, d \in D, t \in N_T \tag{30}$$

$$\delta_{i,t}^{\max} z_{i,t} \le \theta_{i,t} \lambda_{s,d,t}^{cl} \le \delta_{i,t}^{\max} (1 - z_{i,t}) + \theta_{i,t} \lambda^{\max} z_{i,t}, \ \forall i \in C_{s,d,t}, s \in N_s^*, d \in D, t \in N_T \tag{31}$$

$$z_{i,t}^1, z_{i,t}^2, z_{i,t} \in \{0,1\} \tag{32}$$

$$\begin{cases} z_{i,t}^1 = z_{i-1,t}^1, \forall i > 1, i \in C_{s,d,t}, t \in N_T, s \in N_s^*, d \in D \\ z_{i,t}^2 = z_{i-1,t}^2, \forall i > 1, i \in C_{s,d,t}, t \in N_T,, s \in N_s^*, d \in D \end{cases} \tag{33}$$

The objective function (24) is to minimize the total reimbursement paid to customers in period *t*. Constraint (25) represents the total difference between the actual and day-ahead scheduled power consumption. Constraint (26) represents that a power consumption reduction is required in each swap in the congested period t_1. Constraint (27) ensures that the amount of energy rebound in each period and swap does not exceed the limit in FTs. Constraint (28) ensures that a power consumption increase is compensated by a power consumption decrease in each period and each swap. Constraints (29)-(32) model the response of a customer in the transactive market. Constrain (33) ensures that all the customers belonging to the same side of a swap should have the same modification direction of power consumption target in each period.

3) Determination of the price for a swap bid

After solving the above model (OPT.3), the amount of energy rebound ($p_{s,t}^{\mathrm{r}}$) in each swap and each period is obtained and swaps are determined. Then, the aggregator determines the price for each swap using the following equation.

$$\begin{cases} \text{Cost}_s = \sum_{t\in N_T}\sum_{i\in N_c}\sum_{d\in D} b_{i,s,d,t}\theta_{i,t}\left(\lambda_{s,d,t}^{cl}\right)^2, \ \forall s \in N_s^* \\ \text{Pr}_s = c\text{Cost}_s, \ \forall s \in N_s^* \end{cases} \tag{34}$$

where Cost$_s$ is the total paid reimbursement of s-th swap; c is the profit coefficient determined by the aggregator; Pr$_s$ is the price of s-th swap bid.

4.3. Algorithm of the proposed two-tier demand response scheme

```
Algorithm1: Determine FTs
Input: $t_1$: congested period, $f_l$: congested lines and each congested line's loading value exceeding limit, topology of the network
Output: $S^{(1)}$ of the FTs
1.Solve OPT.1

Input: $N_s^*$ : the number of selected swaps, $f^r$: the remaining capacity of uncongested lines, topology of the network
Output: $S^{(2)}$ of the FTs
2. Solve OPT.2

Algorithm 2: Determine swap bids
Repeat: for each period $t$, Initial $t=t_1$
    Input: $K_{i,t_0}$ : initial household temperature one hour before providing flexibilities, $K_{i,t}^{\mathrm{des}}$ : desired temperature, $p_{i,t-1}^{\mathrm{a}}$ : actual HP power consumption of period $t$-1,
    Output: $p_{i,t}^{\mathrm{tar}}$ : HP power consumption target
    3. Solve (23)

    Input: $p_{i,t}^{\mathrm{tar}}$ : HP power consumption target, $\theta_{i,t}$: response curve, $p_{s,t}^{\mathrm{r,max}}$ : limit of the amount of energy rebound, $b_{i,s,d,t}$: mapping matrix
    Output: $p_{s,t}^{\mathrm{r}}$ : the amount of energy rebound, $\lambda_{s,d,t}^{\mathrm{cl}}$ : clearing price
    4. Solve OPT.3

    Input: $\lambda_{s,d,t}^{\mathrm{cl}}$ : clearing price
    Output: $p_{i,t}^{\mathrm{a}}$ : actual HP power consumption
    5. Solve (4) and (5)

    Update: $t=t+1$, update $b_{i,s,d,t}$
Until: all the elements of $b_{i,s,d,t}$ are zero

Input: $\lambda_{s,d,t}^{\mathrm{cl}}$ : clearing price, $\theta_{i,t}$: response curve, $b_{i,s,d,t}$: mapping matrix
Output: Pr$_s$: Prices of swap bids
6. Solve (34)
```

5. Case studies

Case studies were carried out with the distribution network in Figure 1 to demonstrate the effectiveness and benefits of the proposed two-tier DR scheme. The detailed data of load points and line segments can be found in [31]. It is assumed that each customer owns one HP, and there are two aggregators in the study; aggregator 1 has contracts with 80 customers per load point; aggregator 2 has contracts with 120 customers per load point. Customers can be categorized into four types (Type1-Type4) according the response rate θ. It is assumed that customers are willing to rebound energy as soon as possible. Table I lists the key parameters of simulations. The resulting line loadings of L2, L3 and L13 from the day-ahead planning without considering forecast errors are shown in Figure 6.

Table I. Key parameters of simulations

Parameters	Value
COP of HP	2.3
Desired temperature	23 °C
Satisfying temperature range	22.7 -23.3 °C
Line loading limit of L2	1600kW

Line loading limit of L3	7200kW
Line loading limit of L13	9000kW
Resistance/reactance	0.26/0.027 omh/km
Response rate of Type1/2/3/4	0.5/0.4/0.3/0.2 kW/DKK
Lower limit of voltage	0.948 p.u.
Profit coefficient of agg1/agg2	1.3/1.5

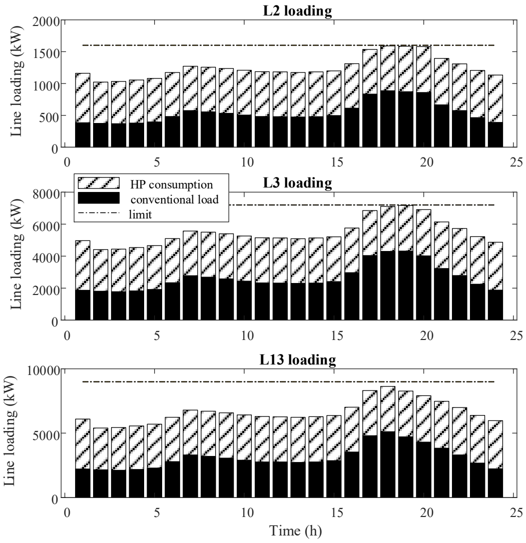

Figure 6. Line loadings from the day-ahead planning

5.1. Congestion management

In this subsection, the effectiveness of the proposed two-tier DR scheme to solve real-time congestion is verified. As approaching 18:00, it is assumed that, due to the day-head forecast errors of the convention load consumption, the DSO predicts that there will be overloading of 100kW in L2 and 80kW in L3 at 18:00 and the overloading will lasts for 1 hour. The forecasted line loadings of L2, L3 and L13 are shown in Figure 7. In order to resolve congestion in L2 and L3, the DSO performs OPT.1 and OPT.2 and forms two FTs as listed in Table II.

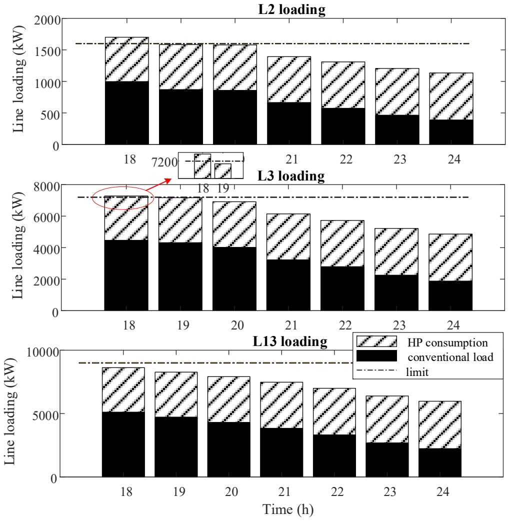

Figure 7. Forecasted line loadings of L2, L3 and L13 at real-time operation

Table II. Flexibility tables

Unit (kW)	Side	Load point	18:00, 1h	19:00, 1h	20:00, 1h	21:00, 1h
FT1	$S_1^{(1)}$	LP$_1$	-100	+, ≤6	+, ≤11	+, ≤ 197
	$S_1^{(2)}$	LP$_{11\text{-}16,\ 18\text{-}25\ 32\text{-}38}$	+100	-, ≤6	-, ≤11	-, ≤ 197

FT2	$S_2^{(1)}$	$LP_{2\text{-}5}$	-100	+, ≤20	+, ≤178	+, ≤ 947
	$S_2^{(2)}$	$LP_{11\text{-}16,\ 18\text{-}25\ 32\text{-}38}$	+100	-, ≤20	-, ≤178	-, ≤ 947

Take the FT1 as an example, FT1 requires that a swap bid should provide a power consumption reduction with the mount of 100kW at LP_1 at 18:00 and at the same time provide opposite flexibilities at $LP_{11\text{-}16}$, $LP_{18\text{-}25}$ and $LP_{32\text{-}38}$. Moreover, the FT1 determines the limits of the amounts of energy rebound in the following periods and requires that swap bids should ensure the system balance. After receiving the FTs, the aggregators interact with their contractual customers to formulate swap bids and each aggregator provides two swap bids as listed in Table III. In the swap market, the DSO chooses the swap bid 1 (S_1) provided by Aggregator 2 and chooses the swap bid 2 (S_2) provided by Aggregator 1 because they have lower prices. Then, Aggregator 1 implements S_2 and Aggregator 2 implements S_1 at the operation time. For example, at 18:00, Aggregator 2 will reduce HP power consumption by 100 kW at LP_1 to resolve congestion and will increase HP power consumption by 100kW at $LP_{11\text{-}12}$ to ensure the system balance. Then, Aggregator 2 will increase HP power consumption at LP_1 by 6kW at 19:00 and by 11kW at 20:00, which allows customers at LP_1 to restore their household temperatures. Moreover, the HP power consumption at $LP_{11\text{-}12}$ is reduced at 19:00 and 20:00 to maintain the system balance. The resulting line loadings of L2, L3 and L13 after implementing the selected swaps are shown in Figure 8, from which it can be seen that congestion in L2 and L3 is resolved at 18:00 and energy rebound does not cause new congestion following 18:00. Therefore, the proposed two-tier DR scheme can resolve real-time congestion efficiently.

Table III. Swap bids provided by the aggregators

Unit (kW)	Swap	Price (DKK)	Side	Load point	18:00, 1h	19:00, 1h	20:00, 1h
Agg.1	S_1	792	$S_1^{(1)}$	LP_1	-100	+6	+11
			$S_1^{(2)}$	$LP_{11\text{-}12}$	+100	-6	-11
	S_2	**375**	**$S_2^{(1)}$**	**$LP_{2\text{-}4}$**	**-100**	**+20**	**+0.86**
			$S_2^{(2)}$	**$LP_{13\text{-}15}$**	**+100**	**-20**	**-0.86**
Agg.2	**S_1**	**527**	**$S_1^{(1)}$**	**LP_1**	**-100**	**+6**	**+11**
			$S_1^{(2)}$	**$LP_{11\text{-}12}$**	**+100**	**-6**	**-11**
	S_2	565	$S_2^{(1)}$	LP_2	-100	+20	+2.13
			$S_2^{(2)}$	$LP_{13\text{-}14}$	+100	-20	-2.13

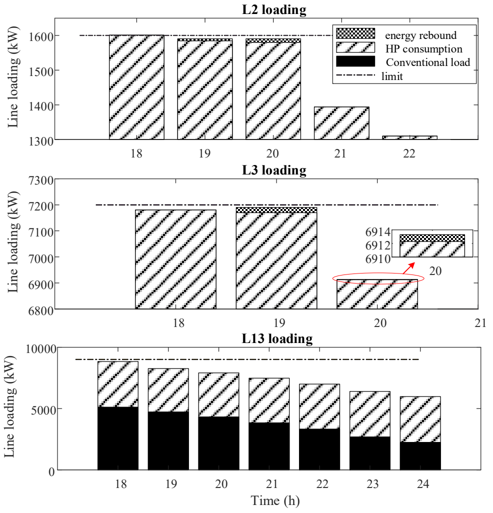

Figure 8. Resulting line loadings after implementing selected swaps

5.2. Customers' requirements on energy rebound

In this subsection, a comparison between the proposed two-tier DR scheme and the existing flexible demand swap (FDS) based DR scheme in [26] was carried out to demonstrate the benefit of the proposed DR scheme, i.e., the proposed two-tier DR scheme can consider customer' requirements on energy rebound. The proposed two-tier DR scheme allows customers to rebound energy in multiple periods and determine the amounts of energy rebound by themselves. As such, customers' specific constraints, e.g., household temperature limits, can be satisfied. It is assumed that the same aggregators implement swaps and the same load points provide flexibilities in the FDS scheme. Therefore, Aggregators 1 and 2 implement the following two swaps, S_1^{FDS} and S_2^{FDS}, respectively, during the operation time to relieve congestion in the FDS scheme.

$$S_1^{FDS}:\begin{cases} S^{(1)}:\{LP_{2-4}\},(18:00,1h,-100kW),(20:00,1h,+100kW) \\ S^{(2)}:\{LP_{13-15}\},(18:00,1h,+100kW),(20:00,1h,-100kW) \end{cases}$$

$$S_2^{FDS}\begin{cases} S^{(1)}:\{LP_1\},(18:00,1h,-100kW),(21:00,1h,+100kW) \\ S^{(2)}:\{LP_{11-12}\},(18:00,1h,+100kW),(21:00,1h,-100kW) \end{cases}$$

After implementing the swaps, the resulting line loading of L2, L3 and L13 in the FDS scheme is shown in Figure 9. It can be seen that congestion is resolved and energy rebound does not cause new congestion. Take Aggregator 2 as an example, at time 18:00, Aggregator 2 in both DR schemes reduces power consumption by 100kW at LP_1 to resolve congestion and increases power consumption at LP_{11-12} by 100kW to ensure the system balance. However, after 18:00, Aggregator 2 in the FDS scheme only allows customers to rebound energy at 21:00 while customers in the proposed two-tier DR scheme can choose to rebound energy at any period after 18:00, e.g., 19:00 and 20:00 shown in Table III, as long as the total amount of energy rebound does not exceed the limit given in FTs. Therefore, the proposed two-tier DR scheme allows customers to rebound energy in multiple periods.

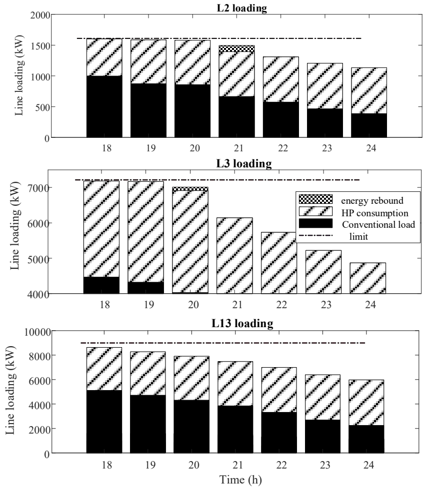

Figure 9. Resulting line loadings of L2, L3 and L13 in the FDS scheme

Without using the transactive control based interactive mechanism, the aggregator in the FDS scheme divides the amount of the required power consumption modification (decrease/increase) into equal units and allocates each unit to each customer. Take a customer located at LP_1 as an example, the amounts of energy rebound and rebound percentages of the customer in both DR schemes are shown in Table IV. The household temperatures of the customer in both DR schemes are shown in Figure 10. It can be seen from Table IV that the customer in the proposed two-tier DR scheme determines the actual amount of energy rebound in each period, i.e., 0.0212 kW at 19:00 and 0.0541 kW at 20:00, and the rebound percentage (15.81%) by itself. However, in the FDS scheme, Aggregator 2 sets the customer to rebound energy with a rebound percentage of 100% (0.833 kW) at 21:00, which neglects the customer's actual needs on the rebound percentage. As a result, in the FDS scheme, the customer's temperature at 21:00 is higher than the satisfying level, as shown in Figure 10, because the required rebound percentage of the customer is lower than 100%. Similarly, the household temperatures and power consumption of a customer located at LP_{11} in both DR scheme are shown in Figures 11 and 12. As shown in Figure 11, at 20:00, the customer's temperature is restored to the satisfying level in both DR schemes. Therefore, the customer should not change its day-ahead scheduled HP power consumption after 20:00. However, in the FDS scheme, due to the energy rebound occurs at LP_1 at 21:00, the customer is set to reduce its power consumption to provide opposite flexibilities to ensure the system balance at 21:00, as shown in Figure 12, which results in a lower temperature than the satisfying level at 21:00, as shown in Figure 11. In summary, the proposed two-tier DR scheme can consider customer's requirements on energy rebound and outperforms the FDS scheme.

Table IV. The amounts of energy rebound of the customer in two DR schemes

Unit (kW)	Time				Reb. percentage
	18:00, 1h	19:00, 1h	20:00, 1h	21:00, 1h	
Two-tier scheme	-0.476(1)	0.0212	0.0541	0	15.81%
FDS scheme	-0.833(1)	0	0	0.833	100%

(1) Notation "-" represents a reduction of HP power consumption

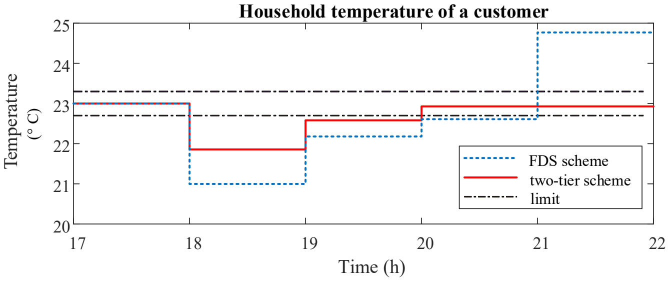

Figure 10. Household temperatures of a customer located at LP_1 in two DR schemes

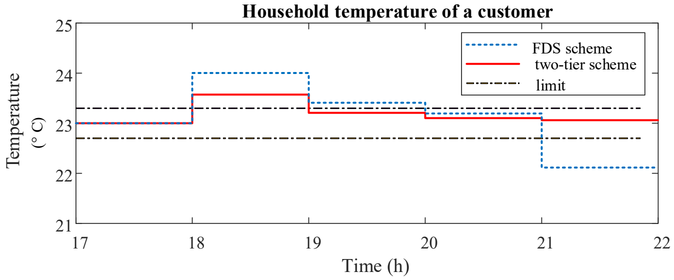

Figure 11. Household temperatures of a customer located at LP_{11} in two DR schemes

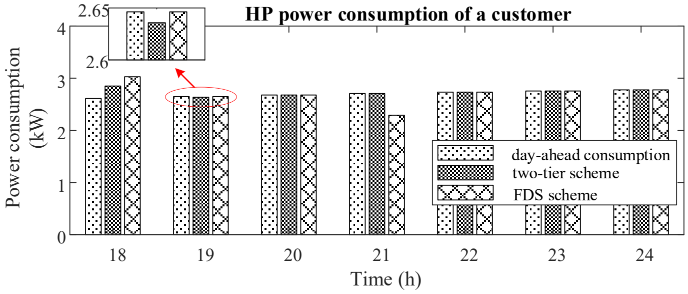

Figure 12. HP power consumption of a customer located at LP_{11} in two DR schemes

5.3. Customer's willingness to provide flexibilities

The simulation results in this subsection demonstrate that the proposed two-tier DR scheme can consider customers' willingness to provide flexibilities. The HP power consumption and household temperatures of two types of customers (Type 1 and Type 4) located at LP_1 are shown in Figures 13 and 14, respectively. As shown in Figure 13, since the Type 1 customer (non-conservative customer) has a larger response rate than the Type 4 customer (conservative customer), the Type 4 customer has smaller modification of its power consumption target (difference between consumption target and actual consumption) at 18:00, 19:00 and 20:00. Accordingly, Type 4 customer' household temperature is restored faster than the Type 1 customer, as shown in Figure 14. To ensure the system balance, customers located at $LP_{11\text{-}12}$ should provide opposite flexibilities. The HP power consumption and household temperatures of Type1 and Type 4 customers locate at LP_{11} are shown in Figures 15 and 16, respectively. Likewise, the conservative (Type 4) customer has less modification of its power consumption target and can restore its household temperature to the satisfying level faster. Therefore, in the proposed two-tier DR scheme, customers' willingness to provide flexibilities is taken into account. Besides, customers can adjust their response curves to change their willingness.

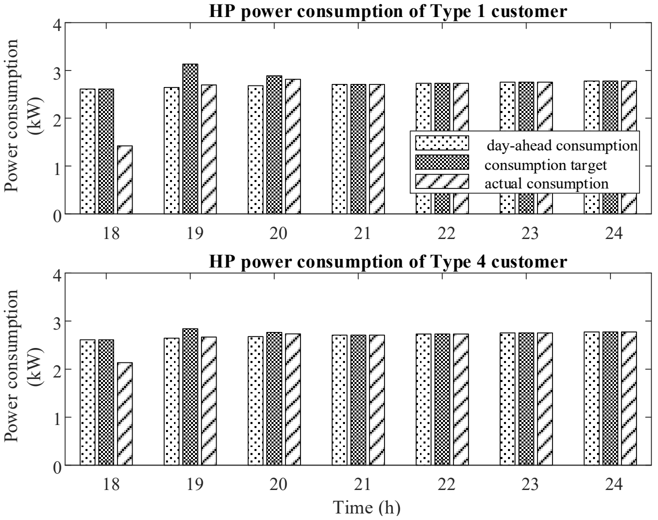

Figure 13. HP power consumption of Type1 and Type 4 customers

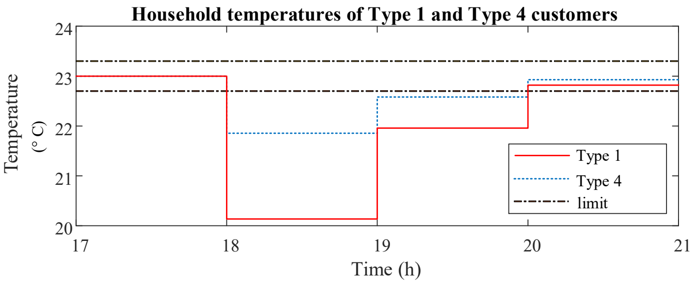

Figure 14. Household temperatures of Type 1 and Type 4 customers

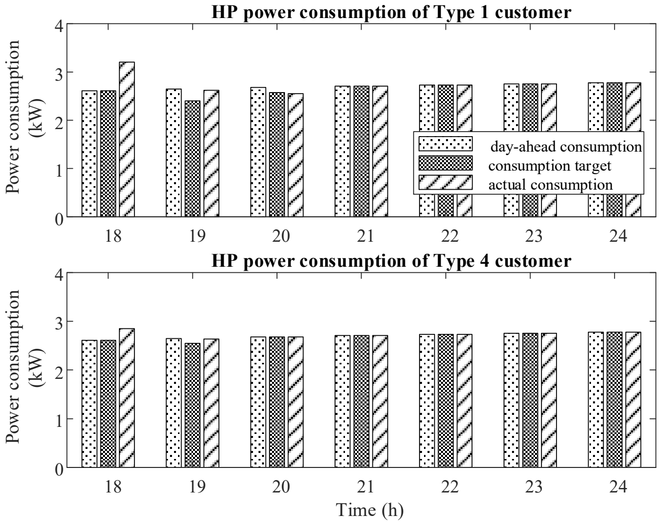

Figure 15. HP power consumption of Type 1 and Type 4 customers

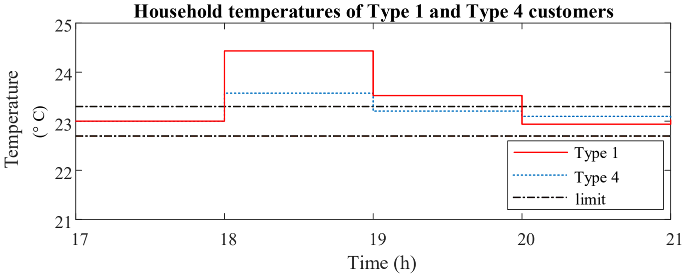

Figure 16. Household temperatures of Type 1 and Type 4 customers

The reimbursement to each type of customer for providing flexibilities is listed in Table V. It can be seen that the most non-conservative customer (Type 1) receives the maximum reimbursement since it provides the largest amount of flexibilities. In the contrast, the most conservative customer (Type 4) receives the least reimbursement.

Table V. Reimbursement for each type of customers and total reimbursement for all customers

Customers	Type1	Type2	Type3	Type4	Total
DKK	3.223	2.578	1.934	1.289	405.617

6. Conclusion

This paper proposes a two-tier demand response scheme with flexible demand swap and transactive control for real-time congestion management in distribution networks. With the flexible demand swap and swap market with the proposed operation mechanism, real-time congestion can be solved efficiently and customers are allowed to rebound energy in multiple periods and determine rebound percentages by themselves. Moreover, a transactive control based interactive mechanism between the aggregators and customers considers customers' willingness to provide flexibilities. The case study results show that the proposed two-tier demand response scheme can resolve real-time congestion efficiently while considering customers' requirements on energy rebound and willingness to provide flexibilities for congestion management. As such, the proposed two-tier demand response scheme is superior to the existing flexible demand swap based demand response scheme.

7. Reference

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