Final report

1. Project details

Project title	Flerlags aggregatløsninger til at lette optimalt efter-spørgsels-respons og gitter
File no.	**64018-0302**
Name of the funding scheme	ERA-NET
Project managing company / institution	DTU Elektro
CVR number (central business register)	30060946
Project partners	None
Submission date	28 January 2022

2. Summary

2.1 Engelsk

The main scope of SMART-MLA is to develop cloud-based multi-layer aggregator ICT solutions to facilitate optimal demand response (DR) and grid flexibility to energy systems to utilize up to 100% renewable energy. It aims to increase the awareness/involvement of consumers/communities on DR aggregating mechanisms in countries even where relevant legislation is still in process. SMART-MLA will demonstrate that at least one layer is applicable to any country regardless of the market structure. Integration of high volumes of intermittent generation and IoT appliances necessitates implementation of ICT based new technologies such as cloud computing, big data and block-chain to add value to DR and improve the grid flexibility (Energy Package 2015). According to the EC proposal for directive on common rules for the IEM, the community aggregators play an important role regarding DR. Therefore, the ICT solutions developed in SMART-MLA will allow customers to take advantages of aggregation.

2.2 Dansk

Det overordnede mål ved SMART-MLA projektet er at udvikle cloud-baserede flerlags aggregator ICT løsninger til muliggørelsen af optimal forbruger deltagelse, kaldet demand response (DR), og fleksibilitet i energi systemer for at kunne udnyttet 100% vedvarende energi. Projektet er rettet mod at forøge forbruger/fællesskabs opmærksomheden og deltagelsen i DR, selv i lande hvor den underlæggende lovgivning stadig er under udarbejdelse. SMART-MLA skal demonstrere at mindst et aggregator lag er gældende i hvilket som helst land, uafhængigt af landets markeds-struktur. Integrationen af store mængder af elproduktion baseret på sporadiske energikilder og IoT enheders udrulning, nødvendiggør implementeringen af nye ICT baserede teknologier, såsom cloud computing, big data og block-chain, da disse teknologier tilføjer værdi til DR og forbedrer fleksibiliteten i elnettet (Energy Package 2015). Ifølge forslaget fra EC om instrukser for fælles regler for IEM, spiller fællesskabs aggregatorer en vigtig rolle i forbindelse

med DR. Derfor skal ICT løsningerne, der udvikles i SMART-MLA projektet, hjælpe forbrugerne med at udnytte denne aggregeringen i fællesskabet.

3. Project objectives

In order to realize the Danish government's ambitions vision of independence of fossil fuels, i.e., energy strategy 2050, it is expected that the large-scale of renewable energy resources (RESs), such as wind power (WP) and solar power (SP), and distributed energy resources (DERs) will be integrated in power systems. The high penetration of DERs, such as electrical vehicles (EVs) and heat pumps (HPs), will challenge the power system's secure operation, especially for distribution networks. Network congestion as the main challenge limits power transfer from one location to another in the network and hinders the integration of DERs, which enables congestion management to be an important task of distribution system operators (DSOs) for secure operation of distribution networks.

Demand response (DR) is considered as a promising way to congestion management. The DR program 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. One of the price-based DR methods include the dynamic tariff (DT) method.

The DT method is a decentralized congestion management method, which is implemented through publishing DTs. The DSO calculates and sends DTs to aggregators, and aggregators independently make their energy plans based on base electricity prices and DTs.

Another type of incentive-based DR scheme is to establish a DR market, i.e., distribution-level flexibility market (DFM). The DFM is a service-oriented platform that facilitates the trading process of flexibility services, such as scheduled re-profiling products (SRPs), from DERs.

The DT can resolve the potential congestion before the day-ahead market clearing while the SRP can be used to alleviate congestion after the day-ahead market clearing if there still exists congestion. The key feature of the DT method is that the optimal energy plans made at the DSO side can be realized at the aggregator side through the DTs. Thus, the effectiveness of the DT method depends on the DT calculation. However, the DT optimization model at the DSO side may be infeasible when severe congestion occurs, resulting in a failure of the DT calculation. In addition, even if the DT calculation is feasible, the DT may be too high under the severe congestion situation.

Integrating the DT and SRP is considered to be a promising way to resolve the above-mentioned issues. The integration of the DT and SRP has not been studied. The integration of the DT and SRP is focused on how to optimally utilize the synergy between the DT and SRP, i.e., how the congestion should be distributed between the DT and SRP.

The project aims to address the identified gap above and develop the hierarchical and distributed framework of the DSO and aggregators in order to facilitate optimal demand response and grid flexibility energy systems up to 100% renewables. An integrated optimization will be developed to optimally use the DT and SRP to alleviate congestion in distribution networks and provide flexibility to the system operator. The project includes three technical work packages:

WP2: Integrated Congestion Management based on DT and SRP

The objective of **WP2** is to integrate the dynamic tariff (DT) and scheduled re-profiling product (SRP) in order to ensure congestion can be efficiently solved and there is a good coordination between the DT and SRP. When the congestion cannot be solved by the DT, i.e., there is no feasible solution for the DT optimization problem, the line capacity constraint will be relaxed in order to get a solution for the DT optimization problem. The solution of the relaxed DT optimization will provide a DT with the relaxed constraint and how much congestion should be handled by the SRP. In case that the DT can solve the congestion, however, the DT is very high, some of the congestion can be solved by the SRP. The optimal percentage of congestion to be solved by the DT is obtained by solving an integrated optimization model of the DT and SRP.

WP3: Transactive Flexibility Market for DSO

The objective of **WP3** is to develop a transactive flexibility market to optimally determine the flexibility amount and prices. The transactive flexibility market will facilitate the demand response to provide flexibility to the system operator. This working package proposes a transactive flexibility market framework, where the price sensitivity of aggregators is modeled by the linear response curve and an alternating direction method of multipliers (ADMM)-based market clearing strategy is used to determine the quantity and price of flexibility. Moreover, an optimal flexibility bidding model for aggregators is formulated, which carefully models the energy pay-back condition and enables the aggregator to receive the maximum revenue with flexibility costs considered.

WP4: Demonstration

The objective of **WP4** is to facilitate the demonstration of the integrated congestion management and transactive flexibility market. The methods developed in this project will be tested and demonstrated. Specially, it is aimed to integrate the algorithms with cloud-based web-service platform through a friendly user interface. The cloud-based web-service platform being developed in the project will provide a web-based environment, which aggregators and DSO can use for implementing demand side management programs and flexibility trading in the TFM.

4. Project implementation

The project evolved as planned and the implementation developed as foreseen and according to milestones agreed upon. There were no major risks in this project. The project did not experience unexpected problems during implementation.

5. Project results

5.1 WP2: Integrated Congestion Management based on DT and SRP.

5.1.1 Framework of Integrating DT and SRP

In the coordinated method, the DT and SRP are used sequentially in the day-ahead time frame, as illustrated in Fig. 5.1.1.1 The procedures of the integrated method to alleviate day-ahead congestion are described as follows,

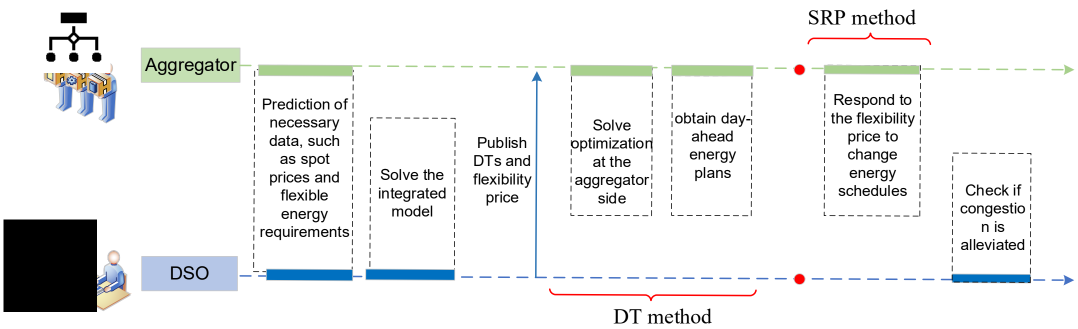

Fig. 5.1.1.1 Framework of the coordination scheme

1) The DSO and aggregators obtain necessary data, such as spot prices, flexible demand energy requirements and customers' response elastic coefficients.

2) The DSO solves the integrated model to calculate DTs and flexibility prices. Then, the DSO sends DTs and flexibility prices to the aggregators.

3) The DT method is carried out at the first step. Based on the DTs and spot prices, the aggregator solves the optimization model to make energy plans.

4) Then, the SRP is used afterward. Based on the flexibility price and response elastic coefficients, each aggregator schedules contractual customers to provide flexibility.

5) After using the DT and SRP, the final day-ahead energy schedules are formulated. Then, the DSO will check if the final energy schedules lead to congestion.

6) Finally, the financial settlement is carried out.

5.1.2 Case Study

5.1.2.1 Grid Data and Simulation Parameters

The effectiveness of the proposed coordination scheme for day-ahead congestion management of active distribution networks was demonstrated with two case on the Bus 4 distribution network of the Roy Billinton Test System (RBTS), as shown in Fig. 5.1.2.1.1. Line segments of feeder 1 are labeled as L1-L12 and load points of feeder 1 are labeled as LP1-LP7. The data of load points is provided in Table 5.1.2.1.1 Load point data. Line loading limits of L2 and L7 are 1110 kW and 3000 kW in case 1, respectively. Line loading limits of L2 and L7 are 1200 kW and 3000 kW in case 2, respectively. It is assumed that each customer at LP1, LP4 and LP5 owns an EV and a HP and has contract with four aggregators (AGG). AGG 1 has contracts with 20 customers per load point, AGG 2 has contracts with 30 customers per load point, AGG 3 has contracts with 30 customers per load point, and AGG4 has contracts with 20 customers per load point. It is assumed that half of customers per load point respond to DTs while the rest of them respond to incentives. The key parameters of EVs and HPs are listed in Table 5.1.2.1.2, and spot price is shown in Fig. 5.1.2.1.2.

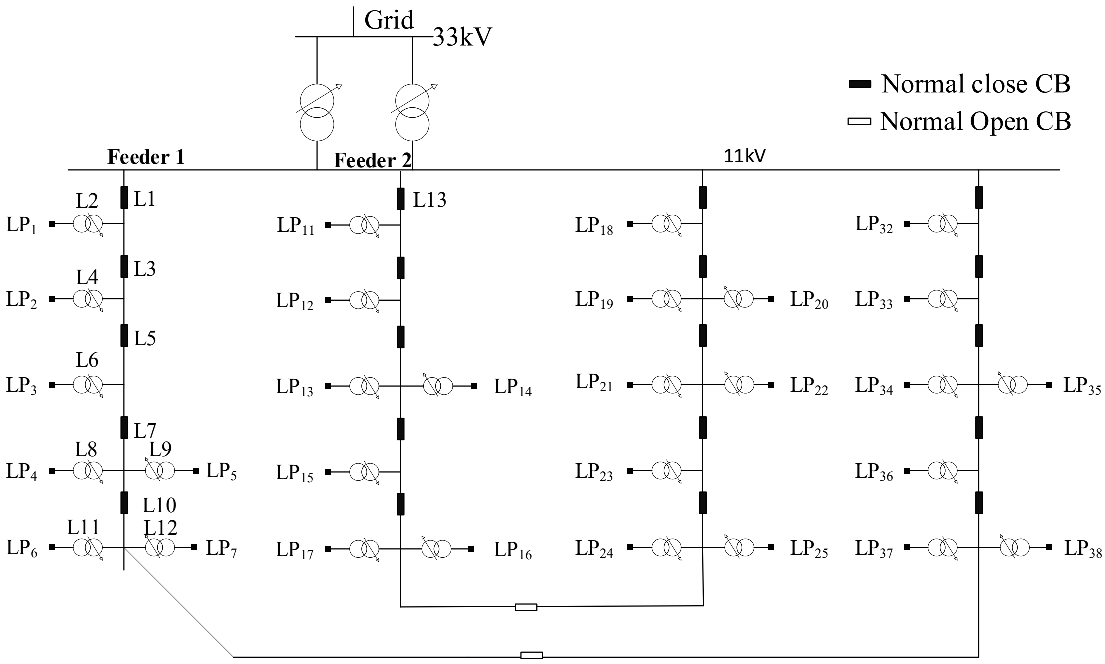

Fig. 5.1.2.1.1 Bus 4 distribution network of the Roy Billinton Test System

Table 5.1.2.1.1 Load point data

load points	customer type	peak conv. load [kW]	number of customers per LP
LP_{1-4},	residential	886.9	100
LP_{5},	residential	813.7	100
LP_{6-7}	commercial	415.0	10

Table 5.1.2.1.2 Key EV and HP parameters

parameter	value
EV battery size	25 kWh
Peak charging power	11 kW (3 phase)
Energy consumption per km	150 Wh/km
Average driving distance	40 km
Minimum SOC	20%
Maximum SOC	85%
COP of HP	2.3
Minimum household inside temperature	20 ºC
Maximum household inside temperature	24 ºC

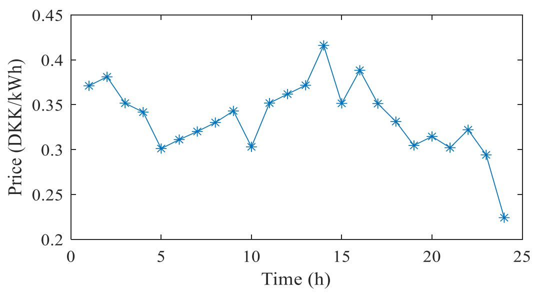

Fig. 5.1.2.1.2. Forecasted spot prices.

Case 1 demonstrates that the relaxed DT model can ensure a feasible solution when the original unrelaxed DT model is feasible and can set a maximum limit to the DTs. In case 2, the DT and SRP are coordinated to resolve congestion. Without congestion management, the line loading on L2 and L7 are shown in Fig. 5.1.2.1.3.

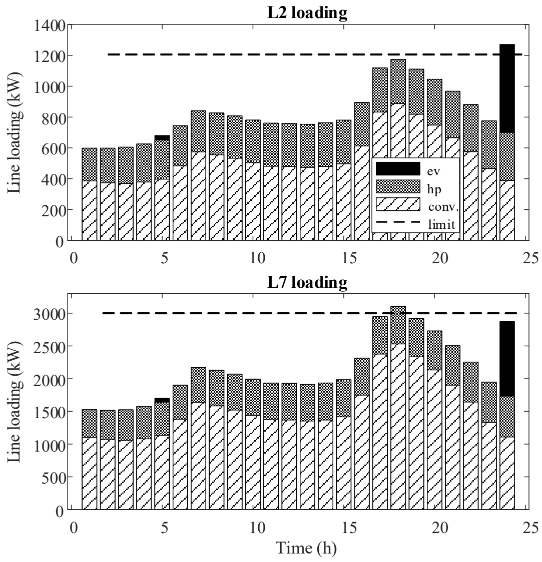

Fig. 5.1.2.1.3. Line loadings on L2 and L7 before congestion management

5.1.2.2 Case 1.

In this case, the original DT model is infeasible due to physical line capacity limits. In order to use the DT to resolve congestion, the relaxed DT model is employed. The penalty coefficient is set as 2, and the line loadings on L2 and L7 are shown in Fig. 5.1.2.2.1. It can be seen that congestion is resolved partially. The DT obtained are listed in Table 5.1.2.2.1. It is shown that the maximum of DTs is limited by using the penalty coefficient. After using SRPs, the congestion can be re-solved completely, as shown in Fig. 5.1.2.2.2.

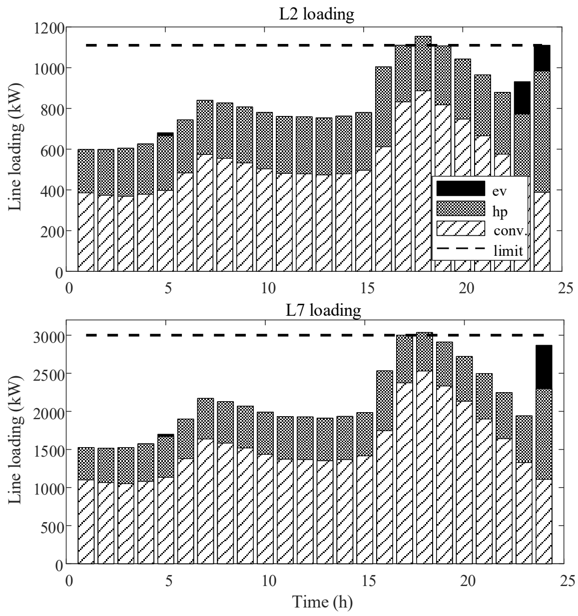

Fig. 5.1.2.2.1 Line loadings on L2 and L7 after using DTs

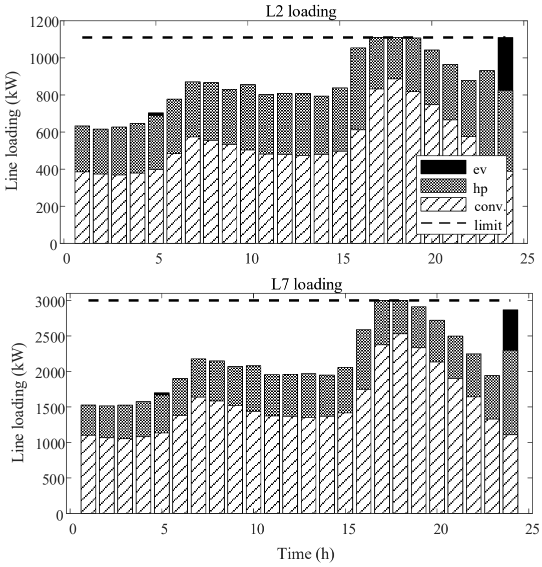

Fig. 5.1.2.2.2 Line loadings on L2 and L7 after using DTs and SRPs

Table 5.1.2.2.1. DTs at load points

Load points	t_{17}	t_{18}	t_{24}
LP1	0.69563	2.0000	0.07024
LP4	0.67176	2.0000	-
LP5	0.67176	2.0000	-

5.1.2.3 Case 2.

In this case, congestion can be alleviated completely by using DTs, but the DTs are too high, as listed in Table 5.1.2.3.1. Therefore, the coordination of the DT and SRP is carried out to resolve congestion with limited DTs. The obtained DTs are listed in Table 5.1.2.3.2, and obtained penalty coefficient is 0.40709.

As shown in Fig. 5.1.2.3.1, congestion on L2 is alleviated completely while part of congestion on L7 is mitigated by using DTs. Then, the SRP is used to alleviate the remaining congestion. The line loadings on L2 and L7 after using SRPs are shown in Fig. 5.1.2.3.2, which demonstrates that the coordination scheme can effectively alleviate congestion. The flexibility prices are 2.55 DKK and 16.15 DKK at t17 and t18, respectively.

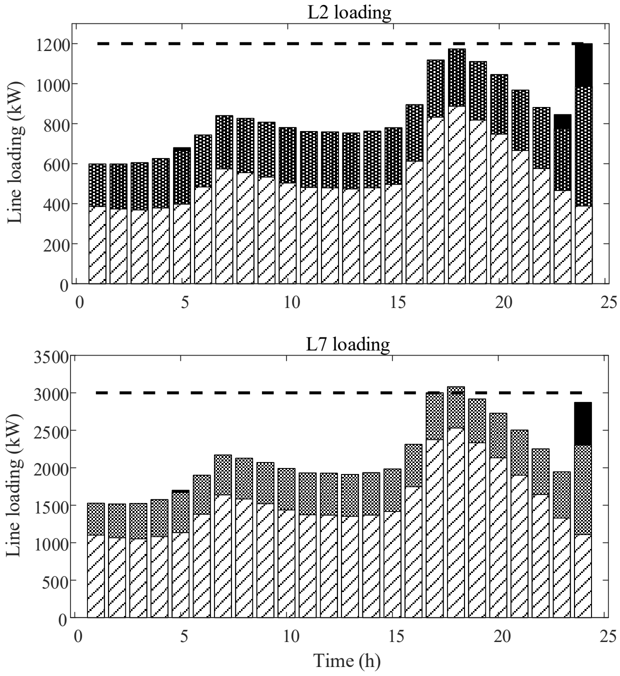

Fig. 5.1.2.3.1 Line loadings on L2 and L7 after using DTs

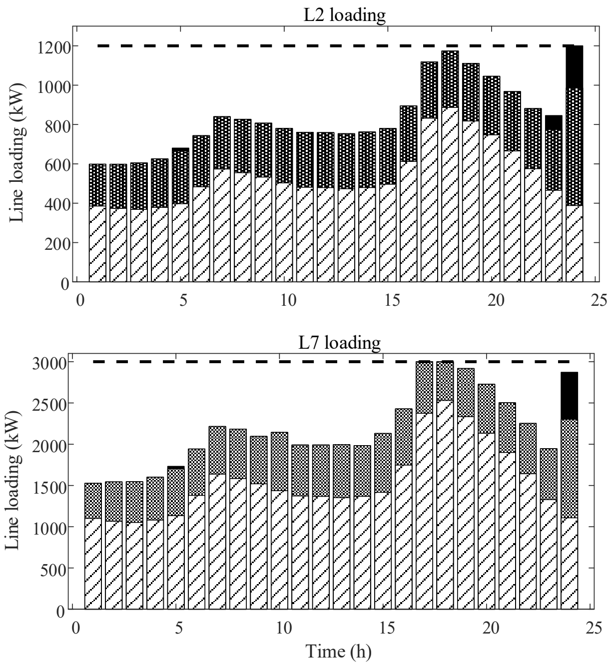

Fig. 5.1.2.3.2 Line loadings on L2 and L7 after using DTs and SRPs

Table 5.1.2.3.1 DTs in the DT method (unit: DKK)

load points	t_{17}	t_{18}	t_{24}
LP_1	-	-	0.06944
LP_4	2.87557	7.31726	-
LP_5	2.87557	7.31726	-

Table 5.1.2.3.2 DTs in the coordination scheme (unit: DKK)

load points	t_{17}	t_{18}	t_{24}
LP_1	-	-	0.06944
LP_4	0.00268	0.40709	-
LP_5	0.00268	0.40709	-

The DSO's revenues or costs in the proposed coordination method are listed in Table 5.1.2.3.3. In the coordination scheme, congestion is distributed between the DTs and SRPs, and the difference between the DSO's revenue and cost is 0.00066 DKK, which is very small and can be ignored. Therefore, the DSO is in the neutral profit position in the coordination scheme.

Table 5.1.2.3.3 The DSO's revenues or costs in the coordination method

unit [DKK]	DT revenues	SRP costs	net revenues
coordination method	1312.65891	1312.65957	0.00066

The PSO solution search processes are shown in Fig. 5.1.2.3.3. and Fig. 5.1.2.3.4. It can be seen that the PSO-based algorithm can gradually obtain better solutions during the search process. In the first 20 generations, the objective function value of the best particle decreases rapidly, whereas it decreases slowly after 20-th generation and remains constant after 60-th generation. As shown in Fig. 5.1.2.3.4, the difference between the DSO's revenue and cost is very small when the final penalty coefficient is applied, which demonstrates that the PSO-based algorithm can obtain a high-quality solution.

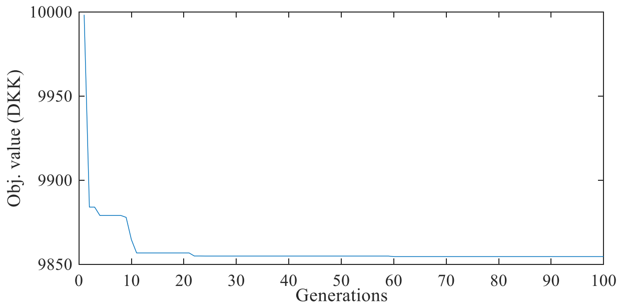

Fig. 5.1.2.3.3 Objection function value of the best solution during the solution search process

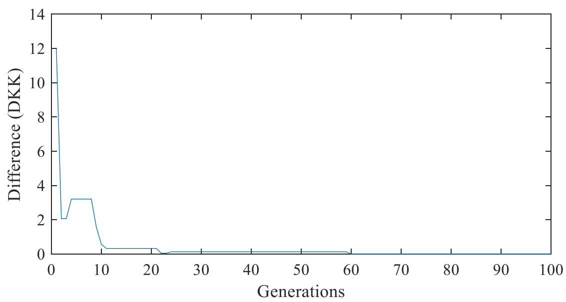

Fig. 5.1.2.3.4 The difference between the DSO's revenue and cost obtained with the best solution during the solution search process

5.2 WP3: Transactive Flexibility Market for DSO

5.2.1 Concept of the Transactive Flexibility Market

The transactive flexibility market (TFM) is a flexibility trading platform where different parties trade flexibility in a geographically limited area, such as a community or a city. A schematic overview of a TFM is shown in Fig. 5.2.1.1. The roles of the participants are described as follows.

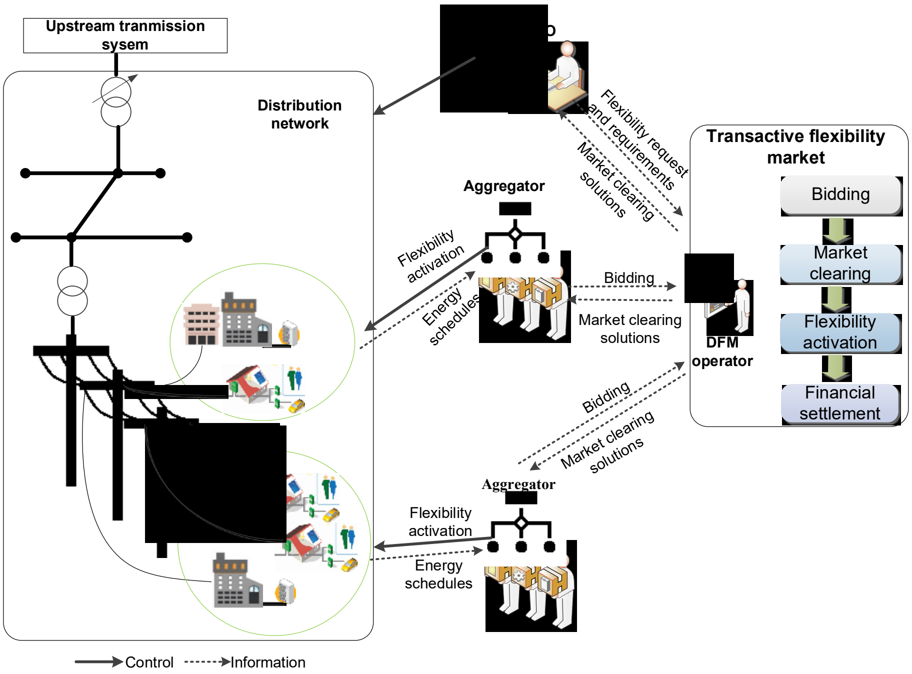

Fig. 5.2.1.1 Schematic overview of the transactive flexibility market

1) DSO: The DSO is responsible for the secure operation of the distribution network. The DSO can procure flexibility in the TFM for different operational purposes, such as congestion management and line loss reduction.

2) Aggregator: The aggregator acts as an intermediary between customers and other TFM participants. Since the individual customer has limited negotiation power in the TFM due to its small volume of flexibility, it is necessary to have an aggregator that can gather flexibility from customers, formulate flexibility service bids, and trade flexibility in the TLM. The aggregator can schedule flexibility sources of customers through contracts between aggregators and customers.

3) Market operator: The TFM operator is an independent entity running the TFM. The TFM operator is responsible for the market clearing process that determines trading results, i.e., the flexibility price and amount of flexibility traded.

The flexibility trading process with the TFM is also shown in Fig. 5.2.1.1. Firstly, after the DSO sends a flexibility request and publishes flexibility requirements, the aggregators formulate flexibility service bids and offer them in the TFM. Secondly, the market operator clears the TFM to determine accepted flexibility service bids to meet the DSO's flexibility requirements. Thirdly, according to the market clearing solution, the aggregators schedule flexibility resources to provide committed flexibility. Finally, flexibility transactions are completed through financial settlement. The DSO pays for flexibility procurement while the aggregators and customers receive revenues for providing flexibility.

5.2.2 Day-Ahead Congestion Management Mechanism with the TFM

The proposed day-ahead congestion management mechanism with the TFM is shown in Fig. 5.2.2.1 and described as follows.

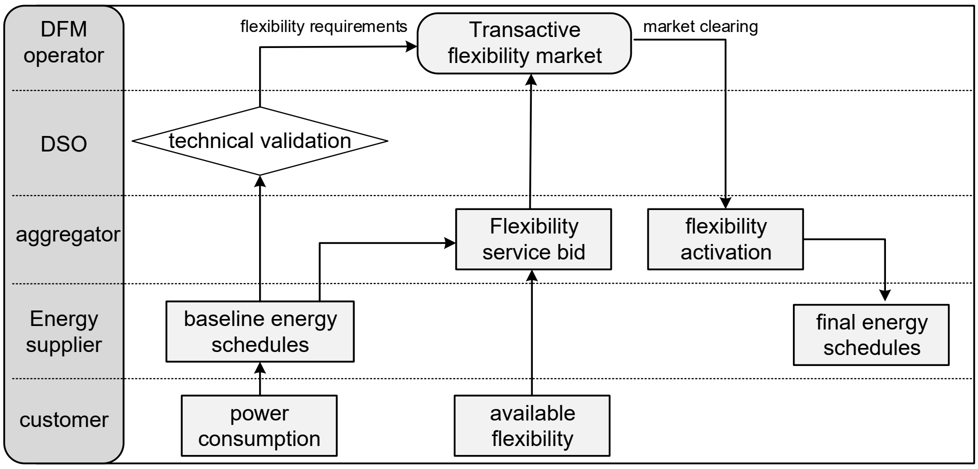

Fig. 5.2.2.1 The proposed day-ahead congestion management mechanism with the TFM

Firstly, based on the forecasted day-ahead spot prices, energy suppliers make baseline energy schedules for customers with the minimum energy costs. The role of the energy supplier is to purchase energy in the day-ahead energy market on behalf of customers. It is assumed that the energy supplier is different from the aggregator; otherwise, the aggregator could intentionally make baseline energy schedules that result in congestion and then make profits by selling flexibility in the TFM to deal with congestion that is originally caused by the aggregator itself.

Secondly, the baseline energy schedules are sent to the DSO for technical validation. The DSO conducts the power flow analysis to examine if the baseline schedules are technically feasible. Once the DSO identifies there is congestion in the following day of operation, the DSO publishes a flexibility requirement table (FRT) in the TFM.

Table 5.2.2.1 Flexibility requirement table

load points	the minimum amount of flexibility required at congestion hours [kW]		allowable payback hours	upper limit of payback percentage	maximum bidding price [DKK/kW]
	t_6	t_{18}			
LP_{4-5}	100	120	t_{21}-t_{24}	150%	1.5 DKK

Table 5.2.2.1 is an example of the FRT, which stipulates congestion hours (t6, t18), candidate load points (LPs) requested to provide flexibility (LP4-5), the minimum amount of flexibility required from LP4-5 at each congestion hour (100 kW at t6, 120 kW at t18), allowable energy payback hours (t21-t24), the upper limit of the energy payback percentage (150%) that is equal to the amount of payback power divided by the amount of flexibility provided, and the maximum bid-ding price (1.5 DKK/kW) at which the DSO is willing to pay for flexibility. The key parameters in the FRT are described below,

- Congestion hours and candidate load points

The DSO can identify congestion hours and lines by conducting the power flow analysis with the baseline energy schedules. According to the topology information, the DSO can find those load points that are able to provide flexibility to resolve congestion.

- The minimum and maximum amount of required flexibility

The minimum and maximum amount of flexibility required are approximate values, which provide a reference for aggregators to provide the appropriate amount of flexibility. The actual amount of flexibility required for resolving congestion is obtained after the TFM clearing. For overload management, the actual amount of flexibility used for resolving overloading issue is equal to the line overload amount. For voltage management, the actual amount of flexibility required at node j for resolving the over/under-voltage issue at node i can be calculated using the nodal voltage deviation from voltage limits at node i and the voltage sensitivity of node i with respect to the power injection at the node j. Therefore, the minimum and maximum amount of flexibility required for voltage management can be obtained according to the amount of flexibility required at each node.

- The upper limit of the energy payback percentage and maximum bidding price

According to historical data of flexibility service bids, the DSO can stipulate the upper limits of the payback percentage and bidding price for the flexibility service bid.

- Allowable energy payback hours

With the approximated maximum amount of flexibility required and upper limit of the payback percentage, the approximated maximum amount of payback power can be calculated, based on which the DSO conducts the power flow analysis to select the allowable payback hours. In these payback hours, energy payback can occur without causing new congestion. To deal with approximation errors when selecting payback hours, a security margin can be reserved when conducting the power flow analysis.

According to the FRT, the aggregators formulate flexibility service bids considering operation constraints of flexibility sources, e.g., EVs and HPs, and submit the bids in the TFM. Table 5.2.2.2 lists two examples of flexibility service bids provided by two aggregators (ag1, ag2) at LP4. The flexibility service bid stipulates the bidding price, amount and locations of flexibility provided at each congestion hour, energy payback hour and amount of payback power. For simplification of the bid formulation, the aggregator is assumed to have payback power at one hour only. After the flexibility bidding process, the market operator clears the TFM to determine accepted bids. With the trading result and baseline energy schedules, the aggregators reschedule flexibility sources to provide committed flexibility. Then, the final energy schedules will be submitted to the day-ahead energy market. Finally, financial settlement regarding flexibility trading is carried out based on the pay-as-bid rule. The DSO pays flexibility procurement costs, and the aggregators receive payments according to bidding prices. Accordingly, the customers receive payments from the aggregators for providing flexibility service.

Table 5.2.2.2. Flexibility service bids

aggregator	**price [DKK/kW]**	**load points**	**the amount of flexibility [kW]**		**payback hour and power [kW]**
			t_6	t_{18}	t_{21}
ag_1	0.55	LP_4	20	30	50
ag_2	0.65	LP_4	30	40	55

5.2.3 Case Studies

Case studies were conducted on the Bus 4 distribution network of the RBTS to demonstrate the effectiveness of day-ahead congestion management with the TFM. The single line diagram of the Bus 4 distribution network is shown in Fig. 5.2.3.1. Line segments of feeder 1 are labeled as L1-L12 and load points are labeled as LP1-7, LP11-16, LP18-25, and LP32-38. The loading limits of L2 and L7, load point data, and key parameters of the EV and HP are listed in Table 5.2.3.1a and Table 5.3.2.1b. Each residential load point has 200 customers, each of which owns an EV and HP to provide flexibility. It is assumed that four aggregators (ag1, ag2, ag3, ag4) participates in the TFM. At each residential load point, each of ag1 and ag4 has contracts with 40 customers, and each of ag2 and ag3 has contracts with 60 customers. The forecasted day-ahead spot price profile is shown in Fig. 5.2.3.2. The lower limit of the voltage magnitude is set to be 0.95 p.u. is order to have a security margin of 0.01 p.u. compared to the assumed physical limit of 0.94 p.u. It is assumed that the bidding prices of aggregators and cost coefficients of EVs and HPs are produced randomly with the normal distribution.

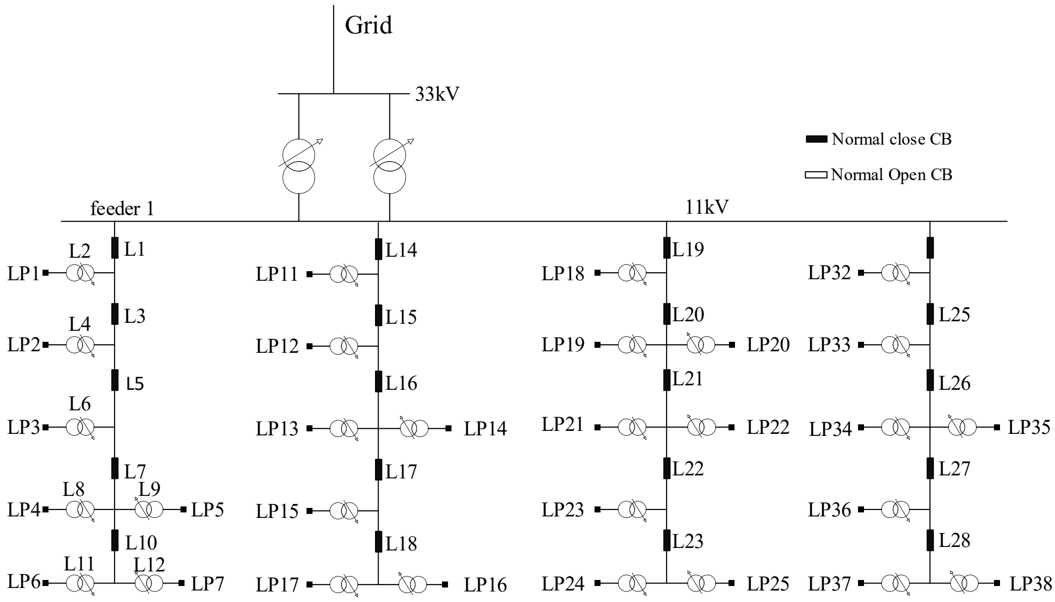

Fig. 5.2.3.1 The single diagram of the Bus 4 distribution network

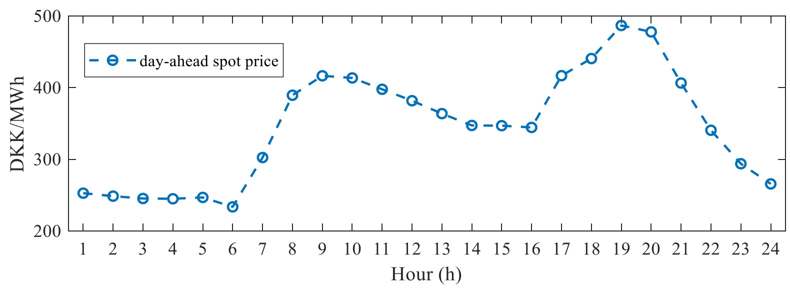

Fig. 5.2.3.2 Forecasted day-ahead spot price profile

Table 5.3.2.1a. Key parameters

Parameters	**Value**
COP of HP	3.0
k_1 (House Type I-V)	0.280/0.315/0.350/0.385/0.420
k_2 (House Type I-V)	3.638/4.093/4.548/5.002/5.457
Lower and upper limits of SOC	20%-90%
Thermal comfort range	20-24 °C
Peak consumption power	6 kW
EV battery size	30 kWh
Energy consumption per km	150 kWh/km
Peak charging power	11 kW
Loading limit of L2/L7	1900/4100 kW
Resistance/reactance	0.26/0.027 omh/km

Table 5.3.2.1b. Load point data

load points (LP)	types of customers	peak conv. load [kW]	number of customers per LP
LP_{1-4}, LP_{11-13}, LP_{18-21}, LP_{32-35}	residential	886.9	200
LP_{5}, LP_{14-15}, LP_{22}, LP_{36}	residential	813.7	200
LP_{23}, LP_{37}	residential	986.9	200
LP_{6-7}, LP_{16-17},	commercial	415.0	10
LP_{24-25}, LP_{38}	commercial	986.9	10

Based on the forecasted day-ahead spot prices, the energy suppliers obtain baseline day-ahead energy schedules and submit the schedules to the DSO for technical validation. The DSO conducts the power flow analysis to identify if the line capacity and voltage magnitude constraints are violated. As shown in Fig. 5.2.3.3, there is an overload of 132.8 kW at L2 at t6, and there are overloads of 378.2 kW and 86.1 kW at L7 at t6 and t18, respectively. As shown in Fig. 5.2.3.4, voltage magnitudes at load points LP23 and LP37 are below the lower limit at t6. To resolve these problems, the DSO needs to procure flexibility in the TFM to perform overload and voltage management. After conducting the power flow analysis and voltage sensitivity analysis, the DSO submits a FRT shown in Table 5.2.3.2 to the TFM.

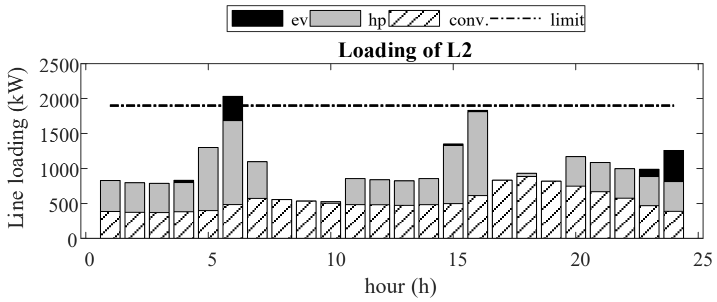

Fig. 5.2.3.3(a) Line loadings of L2

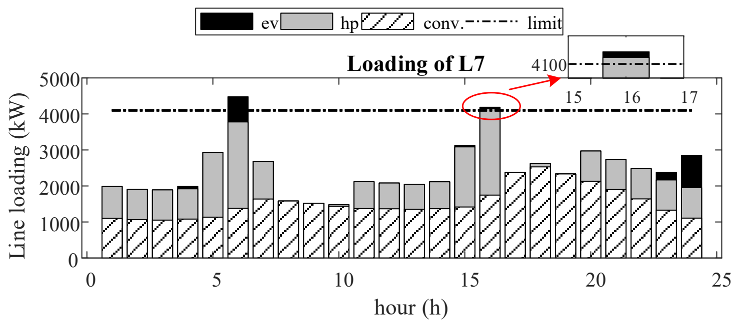

Fig. 5.2.3.3(b) Line loadings of L7

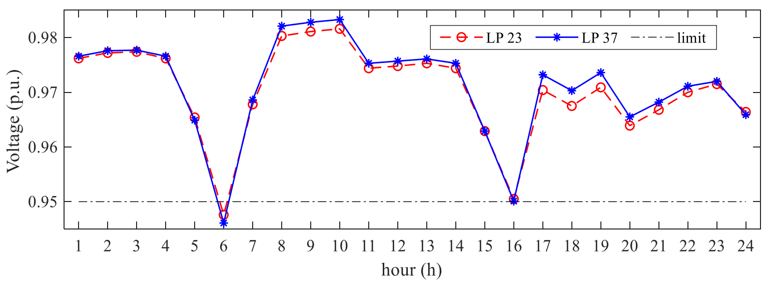

Fig. 5.2.3.4 Voltage magnitudes at LP_{23} and LP_{37}

Table 5.2.3.2 Flexibility requirement table

load points	minimum amount of flexibility required [kW]		payback hours	upper limit on payback percentage	maximum price [DKK/kW]
	t_6	t_{16}			
LP_1	132.8	-	$t_{1\text{-}5}$, $t_{7\text{-}15}$, $t_{17\text{-}24}$	150%	1.5
$LP_{4\text{-}5}$	378.2	86.1	$t_{1\text{-}5}$, $t_{7\text{-}15}$, $t_{17\text{-}24}$		
$LP_{18\text{-}23}$	317.6	-	$t_{1\text{-}5}$, $t_{7\text{-}15}$, $t_{17\text{-}24}$		
$LP_{32\text{-}37}$	433.4	-	$t_{1\text{-}5}$, $t_{7\text{-}15}$, $t_{17\text{-}24}$		

5.2.4 Feeder overload management

Upon the flexibility request, each aggregator solves the optimal flexibility bidding model to formulate flexibility service bids according to the FRT. As listed in Table 5.2.4.1, four aggregators provide flexibility service bids at LP1 and LP4-5 that the DSO can use to resolve congestion on L2 and L7. Specifically, at LP1, four aggregators (ag1-ag4) provide flexibility at t6 and choose to have payback power at t4. At LP4, ag1-ag4 provide flexibility at t6 and t16 simultaneously and require payback power at t10, however, at LP5, ag2-ag4 provide flexibility at t6 only. After the flexibility service bidding process, the market operator clears the TFM to obtain the procurement percentage of each bid, as listed in Table 5.2.4.1. With the market clearing solution, the aggregators reschedule EVs and HPs to provide committed flexibility and formulate the final day-ahead energy schedules. The resulting loadings of L2 and L7 are shown in Fig. 5.2.4.1(a) and Fig. 5.2.4.1(b). It can be seen that congestion on L2 and L7 is resolved and energy payback occurs at t4 and t10 without causing new congestion, which demonstrates the effectiveness of overload management with the TFM.

Table 5.2.4.1. Flexibility service bids

aggregator	price [DKK/kW]	load point	flexibility amount [kW]		payback hour and amount [kW]	
			t_6	t_{16}	t_4	t_{10}
ag_1	0.75	LP_1	60.896	-	66.478	-
	0.62	LP_4	49.673	20.819	-	74.341
	0.70	LP_5	52.857	22.692	-	79.820
ag_2	0.58	LP_1	87.408	-	94.763	-
	0.66	LP_4	78.673	34.506	-	119.152
	0.63	LP_5	89.463		97.047	
ag_3	0.53	LP_1	83.661	-	90.853	-
	0.71	LP_4	81.833	35.373	-	123.723
	0.59	LP_5	84.901	-	92.302	
ag_4	0.84	LP_1	67.318	-	73.219	-
	0.78	LP_4	57.224	24.412	-	85.806
	0.73	LP_5	54.810	-	59.565	-

Table 5.2.4.1. Procurement percentages of flexibility service bids and total amount of purchased flexibility

aggregator	load point	percentage	
		t_6	t_{16}
ag_1	LP_1	-	-
	LP_4	1.000	1.000
	LP_5	0.392	1.000
ag_2	LP_1	0.562	-
	LP_4	1.000	1.000
	LP_5	1.000	-
ag_3	LP_1	1.000	-
	LP_4	-	0.230
	LP_5	1.000	-
ag_4	LP_1	-	-
	LP_4	-	-
	LP_5	1.000	-
total amount [kW]		511.040	86.135

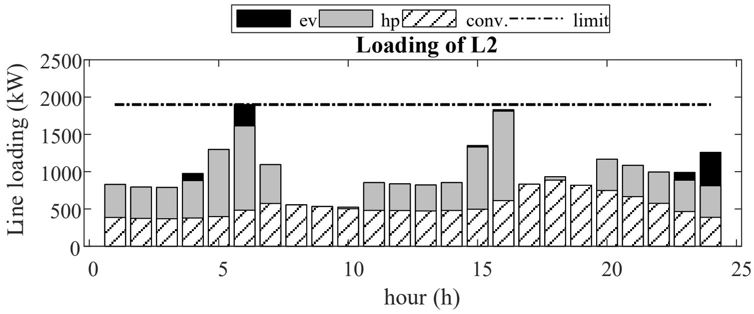

Fig. 5.2.4.1(a) Line loadings of L2 of the final day-ahead energy schedules

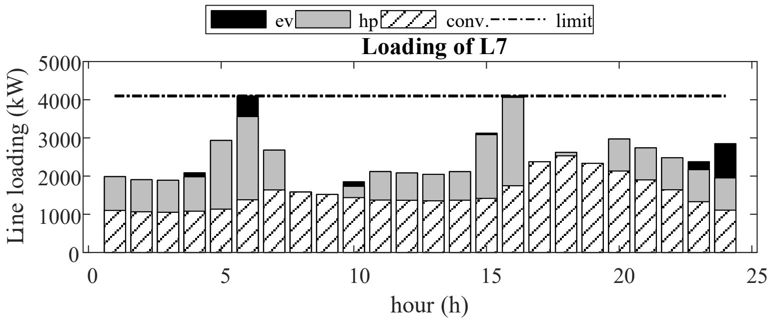

Fig. 5.2.4.1(b) Line loadings of L7 of the final day-ahead energy schedules

The baseline and final charging power profiles and SOC levels of an EV at LP4 are shown in Fig. 5.2.4.2. In order to provide flexibility at t6 and t16, the EV charges more power at t10 so that it can have power consumption reductions at t6 and t16 while maintaining the sufficient SOC level for the daily driving consumption. The baseline and final power consumption profiles of a HP at LP4 and its household inside temperature are shown in Fig. 5.2.4.3. Similarly, the HP decreases power consumption at t6 and t16 to provide flexibility while having payback power at t10 to maintain the household inside temperature within the thermal comfort range.

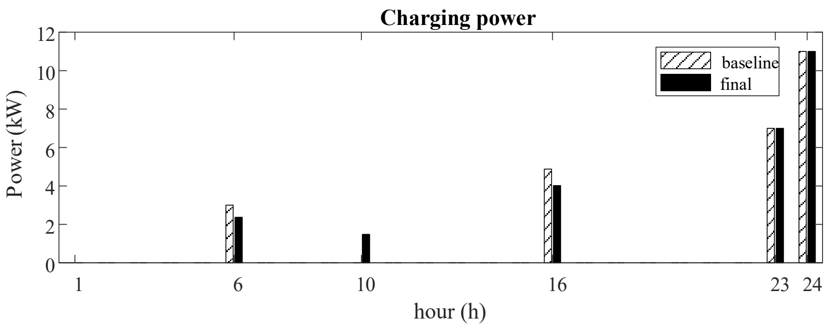

Fig. 5.2.4.2(a) Baseline and final charging power profiles of an EV at LP_4

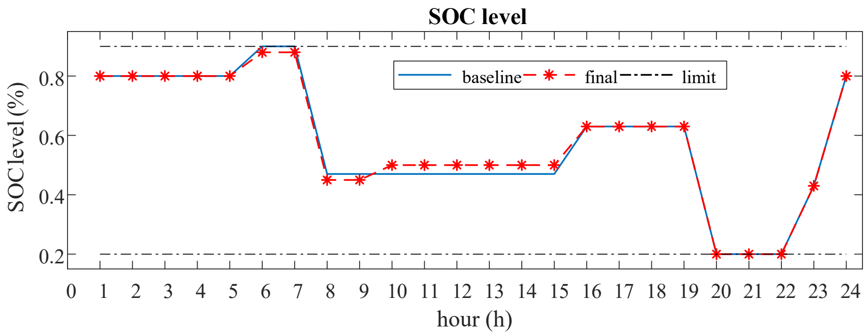

Fig. 5.2.4.2(b) Baseline and final SOC levels of an EV at LP_4

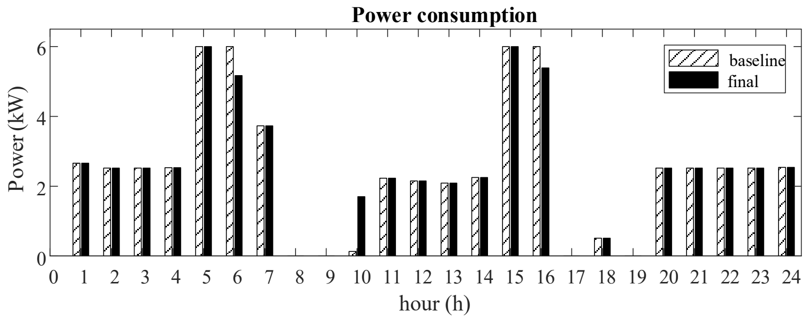

Fig. 5.2.4.3(a) Baseline and final power consumption profiles of an HP at LP_4

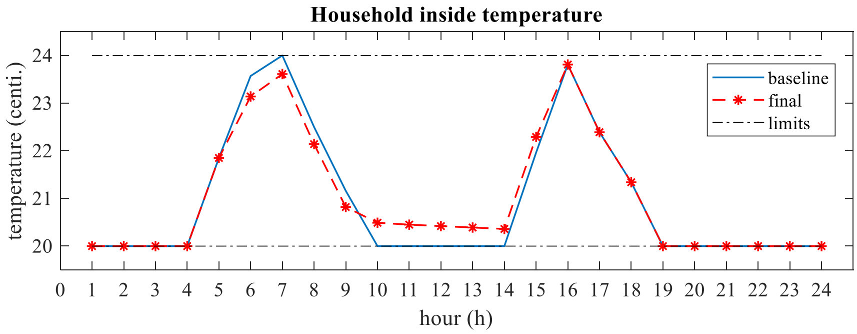

Fig. 5.2.4.3(b) Baseline and final household inside temperature of an HP at LP_4

5.2.5 Feeder voltage management

To perform feeder voltage management, the aggregators formulate flexibility service bids at residential loads LP18-23 and LP32-37. The procurement percentages of the bids accepted in the TFM are listed in Table 5.2.5.1. It is shown that four aggregators provide flexibility at t6 and have payback power at t4. The flexibility of 879.208 kW is purchased in the TFM to resolve under-voltage issues. After rescheduling EVs and HPs, the resulting voltage profiles of LP23 and LP37 are shown in Fig. 5.2.5.1. It is shown that the voltage magnitudes at LP23 and LP37 are above the lower limit at t6 and voltage magnitudes at t4 decrease due to energy payback. In the day-head scheduling horizon, voltage magnitudes and line capacity constraints are respected. Therefore, the proposed TFM is effective to perform voltage management of distribution networks.

In addition, it is important to analyze the voltage linearization error to ensure the voltage security of the market clearing solution. It is shown in Fig. 5.2.5.2 that the maximum difference between the accurate and approximated voltage magnitudes at all load points is 0.00266 p.u. and smaller than the preset security margin of 0.01 p.u.

Table 5.2.5.1. Accepted flexibility service bids and procurement percentage

aggregator	price [DKK/kW]	load points	flexibility amount [kW]	payback hour and power [kW]	procurement percentage
			t_6	t_4	
ag_1	0.69	LP_{23}	59.803	65.197	1.000
	0.72	LP_{37}	59.442	64.848	1.000
ag_2	0.57	LP_{21}	87.923	95.343	0.372
	0.68	LP_{23}	92.910	100.609	1.000
	0.61	LP_{36}	88.942	96.415	1.000
	0.70	LP_{37}	92.393	100.338	1.000
ag_3	0.62	LP_{23}	88.493	96.229	1.000
	0.76	LP_{36}	94.697	102.933	0.738
	0.74	LP_{37}	95.096	103.396	1.000
ag_4	0.63	LP_{23}	58.598	63.457	1.000
	0.66	LP_{36}	60.909	66.258	1.000
	0.83	LP_{37}	66.063	71.658	1.000

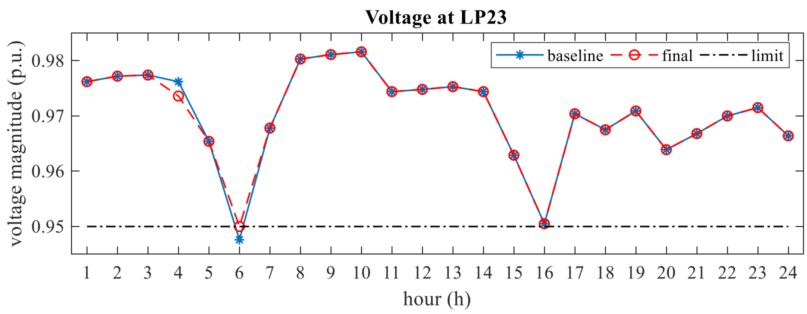

Fig. 5.2.5.1(a) Voltage magnitudes at LP_{23}

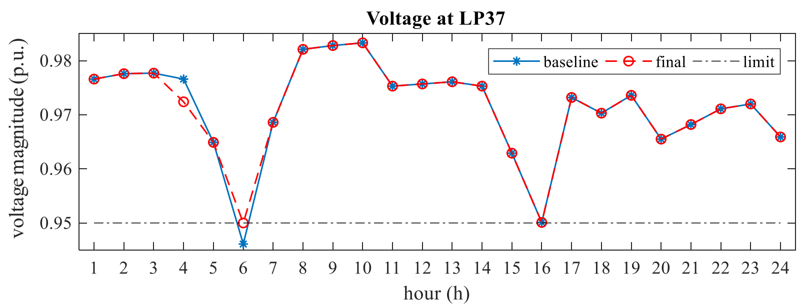

Fig. 5.2.5.1(b) Voltage magnitudes at LP_{37}

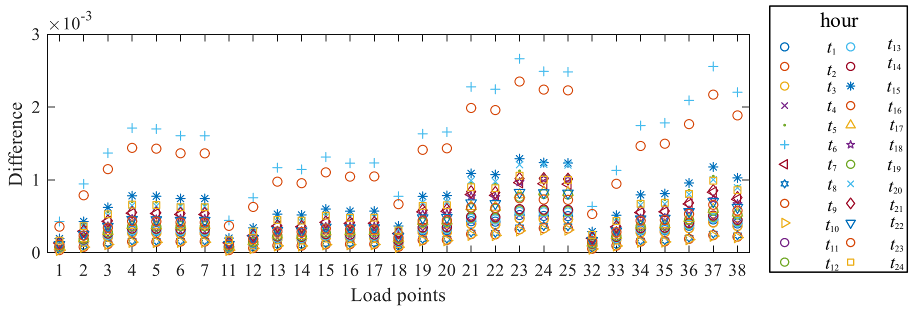

Fig. 5.2.5.2 Differences between the accurate and approximated voltage magnitudes

The charging power profiles and SOC levels of two EVs (ev1 and ev2) at LP23 are shown in Fig. 5.2.5.3 to illustrate the impact of the cost coefficient on providing flexibility. Two EVs have the same driving patterns with different cost coefficients. Since ev1 has a smaller cost coefficient (0.38) than ev2 (0.44), the aggregator tends to utilize flexibility from ev1 in order to gain more revenues. It is shown in Fig. 5.2.5.3 that ev1 provides more flexibility at t6 and needs more payback power at t4 to maintain a sufficient SOC level for driving consumption.

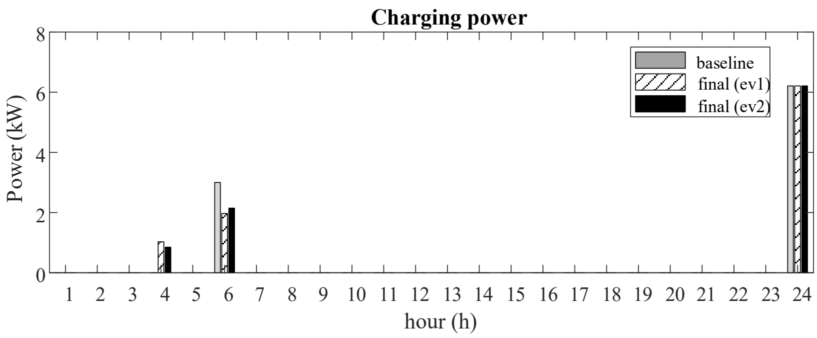

Fig. 5.2.5.3(a) Charging power profiles of two EVs at LP_{23}

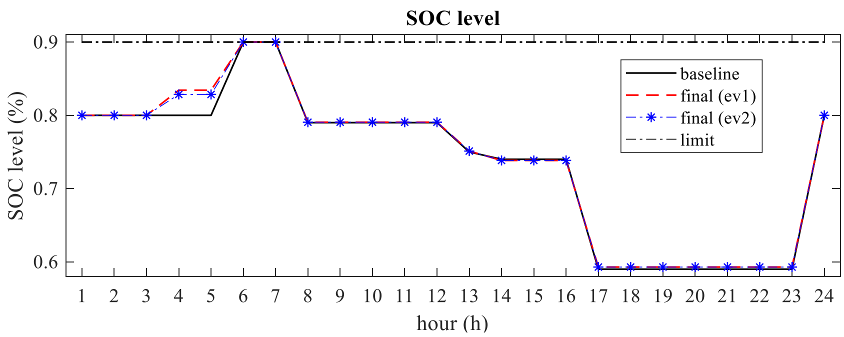

Fig. 5.2.5.3(b) SOC levels of two EVs at LP_{23}

5.2.6 Financial settlement

The last process of the TFM framework is to carry out the financial settlement. In the proposed TFM framework, the DSO pays for the flexibility procurement while the aggregator and customers receive revenues for providing flexibility. Table 5.2.6.1 lists the flexibility procurement cost of the DSO and revenues received by the aggregators and customers. As shown in the capital flow in Fig. 5.2.6.1, customers receive payments from the aggregators because of providing flexibility and increased day-ahead energy costs. Therefore, customers do not need to pay extra money for the increased energy costs and always have revenues when they provide flexibility. The aggregators receive flexibility selling revenues from the market operator or from the DSO directly and pay customers for providing flexibility and increased energy costs. Since the flexibility service bid is formulated with the maximization of the non-negative revenue of the aggregator, it ensures that the aggregator always has revenues as long as its bid is accepted. Therefore, the proposed DFM is an attractive flexibility trading platform because it is profitable for the aggregators and customers.

Table 5.2.6.1. Results of financial settlement

players	DSO costs	Aggregators' revenues				Customers' revenues
		ag_1	ag_2	ag_3	ag_4	
DKK	1136.741	85.256	215.666	171.263	91.639	498.984

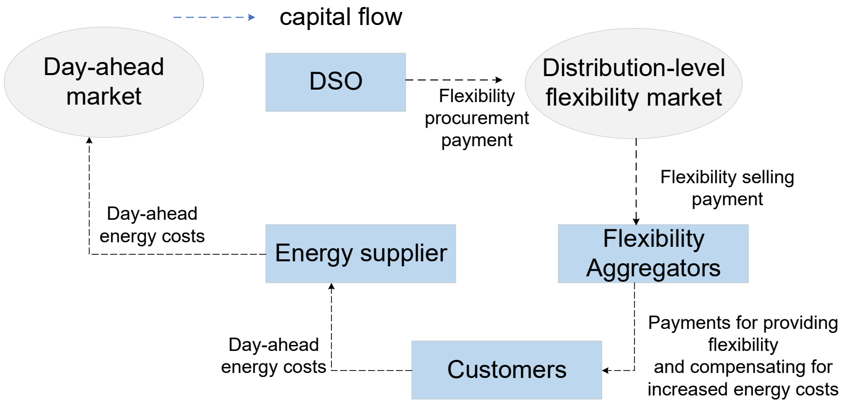

Fig. 5.2.6.1 Capital flow of financial settlement

5.3 WP4: Demonstration

5.3.1 Introduction of the demonstration

SMART MLA considers a multi-layer aggregation approach that covers different structures of markets and regulations. For less developed regions, a simple solution is proposed that monitors the consumption and provide recommendations (Layer 1), while for more developed markets where aggregators are involved in market clearing, we propose optimization and control solutions for DR based on interaction between aggregators and DSOs (Layers 2&3). The whole structure of the project is shown in Fig. 5.3.1.1. As shown in Fig. 5.3.1.1, the first layer deals with consumer/prosumer stage as the first step to attain the benefits of DR programs is to increase awareness level of the customers. As shown in Fig. 5.3.1.1, the second layer deals with customers' demand control and flexibility management between aggregators and consumers. The aggregator acts as an intermediary between customers and the operator of transactive flexibility market (TFM). An optimization model is developed in layer 2 for the aggregator to formulate flexibility service bids considering operational constraints of flexibility sources of customers, e.g., EVs and heat pumps, and submit the bids in the TFM. The flexibility service bid stipulates the bidding price, amount and locations of flexibility provided at each congestion hour, energy payback hour and amount of payback power. As shown in Fig. 5.3.1.1, layer 3 provides a competitive trading platform, i.e., TFM. The TFM is utilized to trade flexibility as commodity between flexibility buyers (i.e., the distribution system operator (DSO)) and flexibility sellers (e.g., the aggregators representing customers). A market clearing model is developed in layer 3. The clearing model determines acceptable flexibility service bids of aggregators to satisfy the DSO's flexibility requirements.

Demonstration in this project means that the products and tools, developed in this project, will be tested in an environment which is as close as one can get to the future market setup. Specially, it is aimed to integrate the algorithms with cloud-based web-service platform through a friendly user interface. The cloud-based web-service platform being developed in the project will provide a web-based environment which aggregators and DSO can use for implementing demand side management programs and flexibility trading in the TFM. The main demonstrations include:

(1) Layer 2-Aggregators with control on customers

The optimization algorithms designed and developed in GAMS for aggregator with control on customers are tested and demonstrated. The optimization algorithms, which run at a server in Turkey, are integrated with database, which is configured at a server in Romania, through a user-interface to demonstrate algorithms on a cloud-based web service. This demonstration of layer 2 shows potential savings of an aggregator which has a control on flexible loads of its consumers.

(2) Layer 3-Local flexibility market for flexibility trading between the DSO and the aggregators

The optimization algorithms designed and developed in GAMS for flexibility trading between the DSO and the aggregators in the TFM are tested and demonstrated. The optimization algorithms, which run at a server in Turkey, are integrated with database, which is configured at a server in Romania, through a user-interface to demonstrate algorithms on a cloud-based web service. The demonstration of layer 3 shows potential savings of aggregators and efficient congestion management of the DSO from flexibility trading in the TFM. It is worth noting that the optimization models for layer 1 are developed by our project partner. Therefore, the demonstration for layer 1 are not presented in this report.

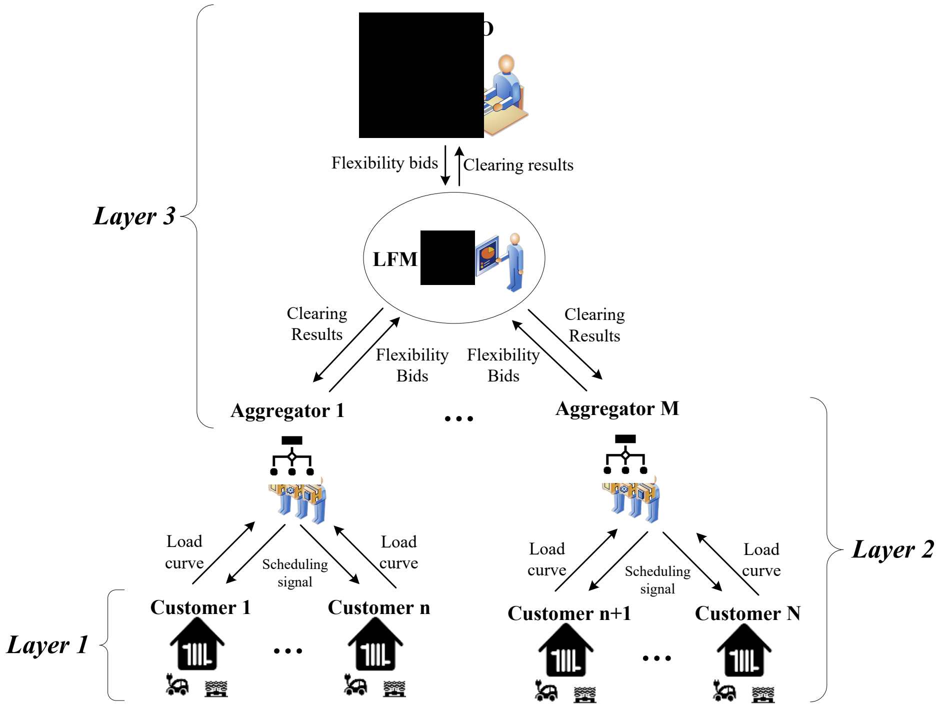

Fig. 5.3.1.1 Structure of the three-layer concept of this project.

5.3.2 Framework of the demonstration

The optimization algorithms developed for layer 2 and layer 3 in this project are demonstrated with the cloud-based web-service platform through interfaces. The framework of the cloud-based web-service platform is shown in Fig. 5.3.2.1. As can be observed, there are three servers, i.e., Optimization server run in Turkey, Database server run in Romania, and the Web server run in Romania, to demonstrate the developed optimization algorithms.

(1) Optimization server

The optimization models developed in this project are run in the optimization server, where the functions of layer 2 and layer 3 are realized. Specifically in layer 2, an optimization model is developed for the aggregator to formulate flexibility service bids considering operational constraints of flexibility sources of customers, e.g., EVs and heat pumps, and submit the bids in the TFM. The flexibility service bid stipulates the bidding price, amount and locations of flexibility provided at each congestion hour, energy payback hour and amount of payback power. After TFM clearing, the aggregators reschedule flexibility sources of customers to provide committed flexibility. In layer 3, an optimization algorithm for market clearing of the TFM is developed. The clearing model determines acceptable flexibility service bids of aggregators to satisfy the DSO's flexibility requirements. To protect the privacy of network parameters, an alternating direction method of multipliers-based market clearing method is developed. With this market clearing method, the operator of TFM communicates with the DSO to clear the market such that the market clearing solution respects network operation constraints without revealing network parameters to the market operator. The optimization server is managed by one of our project partner, Engineering Procurement Research Analysis EPRA, Turkey.

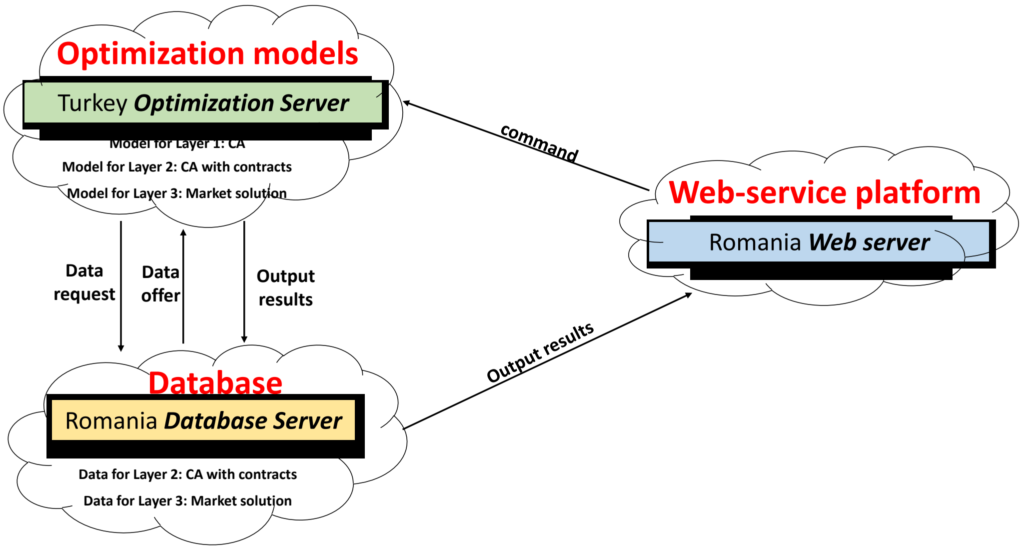

Fig. 5.3.2.1 Framework of the cloud-based web-service demonstration platform.

(2) Database server

All the data is managed and stored in the database, which is specifically designed for the SMART MLA project. As shown in Fig. 5.3.2.2, the data includes the input data for the optimization server and the output data from the optimization server. The optimization server firstly send a data request to the database server to request input data for the optimization models of layer 2 and layer 3. After the optimization algorithms are run in the optimization server, the output data will be stored in the database. These actions are realized through application programming interfaces (APIs) between the optimization server and the database server, as shown in Fig. 5.3.2.2. The APIs are developed using python language. The database server is managed by one of our project partner, Bucharest University of Economic Studies BUES, Romania.

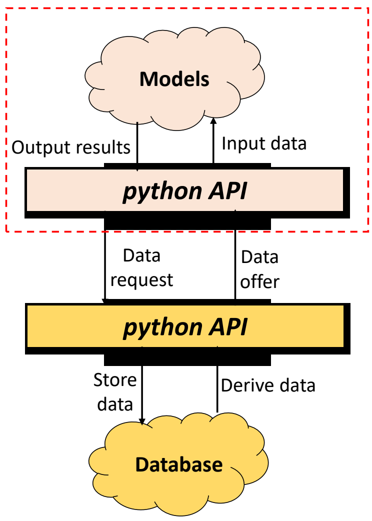

Fig. 5.3.2.2 Schematic of the interface between optimization models and database.

(3) Web server

The web server provides a friendly user interface where users can test the functions of layer 2 and layer 3. For example, a user can log in the web server as an aggregator to test the functions of layer 2. Firstly, the user can send a command to the optimization server to run the optimization model of layer 2 to formulate flexibility service bids considering operational constraints of flexibility sources of customers, e.g., EVs and heat pumps. When the optimization server receives the command from the web server, it calls data from the database server to run the optimization model. Then, the optimization server calculates the optimization results and store the results in the database server. Finally, the database server sends the optimization results to the web server and the web server displays the results to the user.

According to the framework of the cloud-based web-service demonstration platform, there steps have to be implemented to demonstrate the optimization models:

Step 1: A user logs in the web server and sends command to the optimization server.

Step 2: The optimization server runs the optimization models by calling data from the database server. Then, the optimization results are stored in the database.

Step 3: The database server sends the optimization results to the web server. Then, the web server displays the results to the user.

5.3.3 Interfaces of the demonstration

The optimization algorithms are developed in GAMS. And the APIs developed by our project partners connecting the MATLAB functional codes and the database server. Moreover, optimization is becoming widely used in many application areas as can be evidenced by its appearance in software packages such as MATLAB. Although the optimization tools in MATLAB are useful for small-scale nonlinear models, the lack of a capability to compute automatic derivatives makes them impractical for large scale nonlinear optimization. However, modeling languages such as GAMS have had such a capability, and have been used in many practical large scale nonlinear applications. In this context, we developed the interfaces between GAMS and MATLAB to connect the GAMS codes and the database server, as shown in Fig. 5.3.3.1.

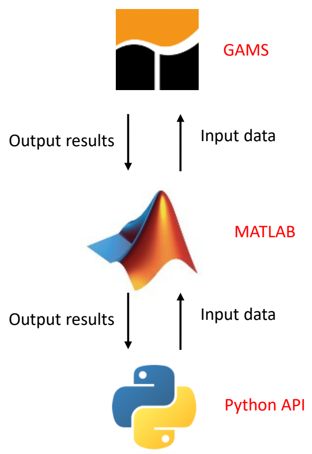

Fig. 5.3.3.1 Schematic of the interface between GAMS and MATLAB.

6. Utilisation of project results

One aim of this project is to improve the business profitability for aggregators in a future with much more volatile power production such as solar and wind. In addition, the methods and relevant software developed in this project are replicable. This means that potential business can be created focus on developing and selling such software to DSOs or flexibility service aggregators. The project did not so far lead to increased turnover, exports, employment and additional private investments. There were no commercialization activities in this project. The project results have been disseminated in journal articles, conference presentation and articles, and book chapters (See Appendix).

7. Project conclusion and perspective

Here are the main conclusions that can be derived from the project results:

(1) Optimization models for optimal coordination between the DT and SRP

The DT can resolve the potential congestion before the day-ahead market clearing while the SRP can be used to alleviate congestion after the day-ahead market clearing if there still exists congestion. Therefore, integrating the DT and SRP is considered a promising way to resolve congestion in distribution networks. However, the optimal integration of the DT and SRP has not been studied. In this project, we developed optimization models for the optimal coordination between the DT and SRP. In case the DT cannot resolve all the potential congestion, a constraint relaxation DT method has been developed to calculate the DTs. The unsolved congestion is then handled by the SRP. If the congestion can be solved by the DT method but the DT is too high, the optimal percentage of congestion to be solved by the DT is obtained by solving the integrated optimization model of the DT and SRP. With the proposed optimal coordination model, congestion can be distributed between the DTs and SRPs, and the DSO can stay in the neutral profit position in the coordination scheme.

(2) Optimization models for TFM

In the existing optimization models for TFM, a few major drawbacks hinder the application of the TFM to day-ahead congestion management:

- The determinations of the flexibility price and amount in the TFM have not been well studied.
- The market operator is assumed to have access to network parameters such that the market clearing solution satisfies network operation constraints, which compromises the privacy information protection;
- The energy payback conditions of flexibility resources are usually determined without considering operational constraints;
- The flexibility cost of flexibility resources has not been considered.

In this project, we developed the optimization models for TFM to overcome the drawbacks:

- In this project an ADMM-based market clearing strategy is proposed, in which the market operator communicates with the DSO to clear the market such that the market clearing solution respects network operation constraints without revealing network parameters to the market operator and the optimal flexibility price and amount are decided.
- This project proposes an optimal flexibility bidding strategy for aggregators. The optimal flexibility bidding problem is formulated as a MIQP model, which carefully models energy payback conditions and enables the aggregator to receive the maximum revenue with the flexibility cost considered. The case studies results demonstrate that the proposed TFM framework can perform effective day-ahead congestion management, including overload and voltage management. The proposed ADMM-based market clearing strategy can efficiently solve the market clearing problem.

(3) Demonstration

A cloud-based web-service platform has been developed in the project which provides a web-based environment which aggregators and DSO. The developed optimization models have been tested and demonstrated. The optimization algorithms to be demonstrated are developed in GAMS. And the APIs developed by our project partners connect the MATLAB functional codes and the database server. Therefore, we also developed the interfaces between GAMS and MATLAB to connect the GAMS codes and the database server. Two main demonstrations are conducted:

• The optimization algorithms designed and developed in GAMS for aggregator with control on customers are tested and demonstrated. The optimization algorithms, which run at a server in Turkey, are integrated with database, which is configured at a server in Romania, through a user-interface to demonstrate algorithms on a cloud-based web service. This demonstration of layer 2 shows potential savings of an aggregator which has a control on flexible loads of its consumers.

• The optimization algorithms designed and developed in GAMS for flexibility trading between the DSO and the aggregators in the TFM are tested and demonstrated. The demonstration of layer 3 shows potential savings of aggregators and efficient congestion management of the DSO from flexibility trading in the TFM.

8. Appendix

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