



FLECH: A Danish market solution for DSO congestion management through DER flexibility services

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Abstract Future electric power systems will face new operational challenges due to the high penetration of distributed energy resources (DERs). In Denmark, distribution system operator (DSO) expects a significant congestion increased in distribution grids. In order to manage these congestions and mobilize the DERs as economically efficient as possible in the future distribution grid, the brand new notion of flexibility clearing house (FLECH) is proposed in this paper. With the aggregator-based offers, the proposed FLECH market has the ability to promote small scale DERs (upto 5 MW) for actively participating in trading flexibility services, which are stipulated accommodating the various requirements of DSO. Accordingly, the trading setups and processes of the FLECH market are also illustrated in detail. A quantitative example is utilized to illustrate the formulation and classification of flexibility services provided by the DERs in the proposed FLECH market.

Keywords Electricity market, Distributed energy resources (DERs), Aggregator, Flexibility clearing house (FLECH), Flexibility services

1 Introduction

In the long term perspective, the renewable energy (wind, photovoltaic, etc.) and more efficient energy

resources (combined heat and power, heat pump, electric vehicle, etc.) will critically improve the security of energy supply by drawing upon sustainable natural sources and reducing environmental impacts [1, 2]. The vast majority of previous and ongoing renewable energy resources and smart grid projects have focused on demonstrating the technical feasibility of these distributed energy resources (DERs) [3, 4] in the distribution grids. The high penetration of DERs is considerably observed worldwide. For instance, by 2020, the share of renewable energy in Denmark must be increased to at least 35 % of final energy consumption—50 % of electricity consumption supplied by wind power [5, 6].

In Denmark and other European Union (EU) countries, the rapid growth of these intermittent DERs will pose a significant challenge associated with congestion issues in distribution grids. Currently, depending on the existing electricity market structure, there are exclusively several approaches for congestion management specific to transmission system operator (TSO), which could be categorized into three types: (1) The optimal power flow (OPF) based method, which is based on a centralized optimization and is considered to be the most accurate and effective congestion management method. (2) The price area congestion control method, which eliminates congestions by generation rescheduling schemes according to congestion price-signals refer to the framework of OPF [7]. (3) The transaction based method, which incorporates the support of point-to-point tariffs for pool markets, based on pay as bid mechanism to provide price signals to promote the maximum use of the existing transmission network. However these congestion management approaches may not appropriate to the distribution grid with two principal reasons: (1) The existing market price system may not fully cover the benefit of DER owners. (2) Dispatching of distribution network is more complex due to a large amount of

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small scale fluctuating DERs with high diversity and dispersal allocation.

Concerning that, the further development and innovation of electricity market will play an essential role on utilizing the DERs as economically efficient as possible.

Over the past decade, with the emerging new market player of virtual power plant (VPP), researches are mainly emphasized on enabling DERs to participate in the existing market, especially to provide different kinds of ancillary services to TSO. The EU project FENIX defines VPP as a flexible representation of a portfolio of DERs that can be used to make contracts in the wholesale market and to offer services to the system operator [8]. There are two types of VPP, the commercial VPP (CVPP) and the technical VPP (TVPP). The CVPP is a competitive market actor that manages the DER portfolios to make optimal decisions on participation in wholesale markets. The TVPP aggregates and models the response characteristics of a system containing DERs, controllable loads and networks within a single grid [9]. In other words, the CVPP optimizes its portfolio with reference to the wholesale markets, and passes DER schedules and operating parameters to the TVPP. The TVPP uses input from the CVPPs operating in its area to manage any local network constraints and determine the characteristics of the entire local network at the grid supply points [10]. Thus, the role of TVPP in distribution networks is the same as the TSO's role in transmission systems.

In recent years, aiming to stimulate the small scale DERs into the existing market structure, the real-time market demonstrated with several ongoing smart grid projects subdivides the time scale into 5 min intervals for providing balancing services to TSO, e.g. the EcoGrid EU market complies with a bidless clearing process, the Olympic Peninsula market and the PowerMatcher energy management system employ agents to submit bids to an auction for establishing an equilibrium price [2].

However, these frameworks may not be consistent with the future scenarios: The primary task of TSO is to avoid system-wide imbalance occurring, while the executive issue for DSO is to relieve the congestions in local network. In addition, the size limitations are often cited as another large barrier for small scale DERs (upto 5 MW) to access the wholesale electricity market, e.g. 10 MW in Nordpool market. Therefore, we have to pave a novel way for fully utilizing the advantages of small scale DERs—Focusing on the distribution grid, proper coordination and activation of consumers and DERs will provide more flexibility in ancillary services, which can enhance economical efficiency and reliability of distribution system.

In this paper, a FLECH market is proposed to give a shot for the feasibility of promoting small scale DERs to participate in flexibility services trading. With the aggregator-based service offers, the proposed FLECH market will

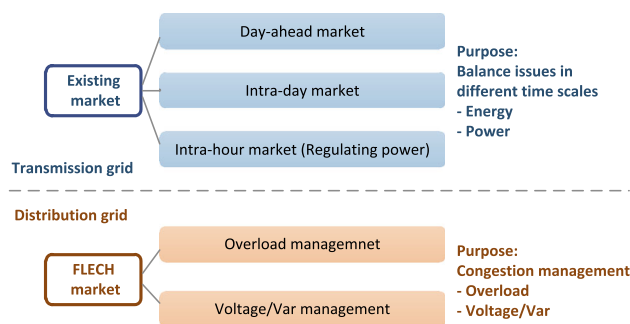


Fig. 1 Scope of the existing market and FLECH market

easily satisfy the congestion management of DSO and benefit DER owners, while further facilitate the integration of DERs into power system. Meanwhile, the flexibility services provided by DERs will expand the properties of existing ancillary services, conducive to the security and stability of distribution network.

2 FLECH market

2.1 Scope

The existing wholesale electricity trade in Nordic power system is NordPool, which consists of day-ahead market, intra-day market, and intra-hour (regulating power) market corresponding to different balancing issues in various time scales, as shown in Fig. 1. The first settlement between energy supply and demand in a given hour (in next 24 h) of operation happens in the day-ahead market, then the price where the expected production meets the predicted consumption is obtained. This price commonly referred to system price or spot price. Obviously, as the hour of operation approaches, this targeted balance might need adjustment as the expectations regarding power plant schedule changes or demand fluctuations. Therefore, a new settlement between production and consumption is obtained, first on the intra-day energy market and then on the intra-hour regulating power market. The regulating power market is responsible for physical electricity trading in 15–60 min prior to the hour of operation.

With the high penetration of DERs and massive growth of smart grid projects, congestion becomes one of the most challenging operation issues in Danish distribution grid. The proposed FLECH market is a parallel running market with the existing markets specializing in the distribution grid, in order to assist DSO to mitigate the congestions and revitalize the DER economy, which is depicted in Fig. 1 as well. Generally, the main congestion management could be classified as follows:

- 1) Feeder overload management: The high power flow comes over feeder capacity-limit, which can be caused by regular growth in electricity consumption, mobilization of reserve capacity in the grid, activation of regulating power for the TSO, or very low prices of electricity.
- 2) Feeder voltage/Var management: The oscillations of voltage and issues of reactive power can be exceeded the band of feeder deviation limits, which normally caused by the variations of local generation or demand.

2.2 Architecture

The parallel architecture of the proposed FLECH market with existing market is shown in Fig. 2. The demand-side DERs and consumers can be re-categorized as flexibility provider and ordinary electricity consumer. The aggregators will harvest the individual flexibility to formulate various types of flexibility services and trade in FLECH market to satisfy the appropriate requirements of DSO congestion management, illustrated in the left dashed box of Fig. 2. As indicated in the right portion, the wholesale electricity produced by conventional supply and delivered through TSO is still settled in the existing market with balance responsible party, further consumed by the ordinary electricity demand via retailers as usual. Therefore, the FLECH market and the existing market could coexist in time and space focusing on different issues of congestion and balance, respectively. It could be also observed that the aggregator and flexibility clearing house (FLECH) are the brand new participants.

- 1) The aggregator, which is a new commercial player, has three basic functions:
 - Assemble and mobilize the flexibility of DERs, pack and schedule flexibilities from individual DER, and provide the service offers to the highest possible bidder with contract.
 - Have thorough knowledge of the electricity markets, put the right price on the flexibility services, and represent DERs to trade in FLECH market.
 - Paid by the DSO for delivering flexibility services. From this payment the aggregator will pay his affiliated DERs according to their contractual agreements.
- 2) The FLECH: which is an independent non-profit driven entity, also responsible for:
 - Make the standardized contracts with DSO and aggregators by stipulating service category.

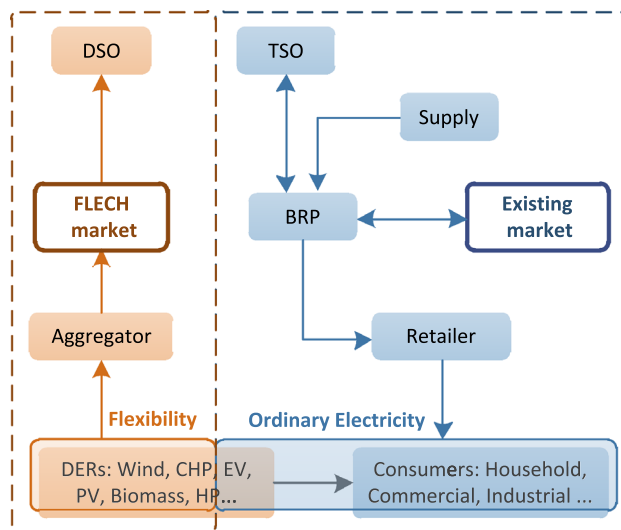


Fig. 2 Parallel architecture of the FLECH market and the existing market

Table 1 The liquidity features of FLECH market

Factors	Liquidity
Energy/power flow	DERs → Aggregator → DSO
Capital flow	DSO → FLECH → Aggregator → DERs
Control signal	DSO → Aggregator → DERs
Information signal	DSO ↔ FLECH ↔ Aggregator ↔ DERs
Physical network	DERs → Distribution grid

- Ensure the FLECH market integrity by mitigating counterparty default risk, and monitors the contracts are being carried out more targeted and efficiently.
- Provide clearing of all contracts traded on the exchange, which is an ex post financial settlement.

It could be further observed that the framework of FLECH market is concise and efficient, in which the supplier is DERs while the consumer is DSO, totally inverts the roles with the prevailing market. Correspondingly, the new liquidity features of FLECH market can be summarized in Table 1.

3 Market trading

3.1 Trading setups

The core missions for FLECH are contracts regulation and ex post financial settlement, there are two possible trading setups and identified as follows:

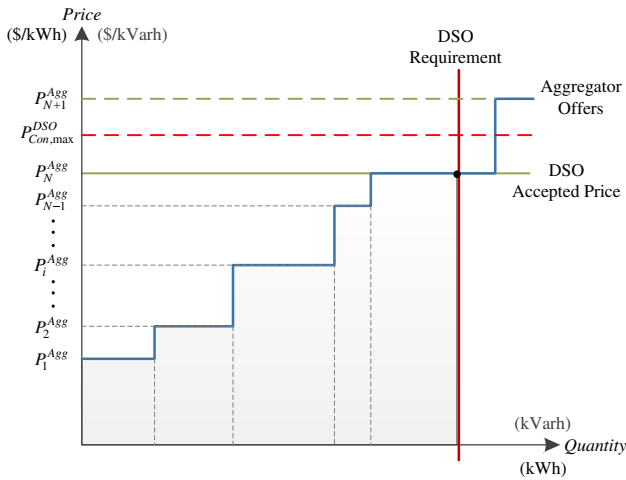


Fig. 3 Single-side aggregator auctions (SAA)

1) Single-side aggregator auctions (SAA): With the vast volume in trading flexibility services, an auction-based setup will arise. The DSO proposes the request quantity of each sort of flexibility service, and the aggregators will submit the offers to satisfy the corresponding services of DSO. Finally, the DSO chooses the available offers appropriately from the aggregators, and the standardized contracts are automatically formed according to the market-rules of FLECH.

More precisely, this trading setup could be referred to SAA. Offers from aggregators are ranked in increasing order and accepted beginning with the least expensive and continuing until the DSO is satisfied, as what illustrated in Fig. 3.

The marginal price for each aggregator offer block can be calculated by

$$P_i^{Agg} = (C_i^R + C_i^A + C_i^O + C_i^P + C_i^{Au}) / Q_i^{Agg}, \quad i \in M \tag{1}$$

where M is the total number of the aggregators to participating in SAA; for i th aggregator, P_i^{Agg} is the marginal price of a certain type of flexibility service (\$/kWh)/(\$/kVarh); C_i^R is the service reservation cost (\$); C_i^A is the total amount of activation cost (\$); C_i^O is the operation cost on assembling, scheduling, mobilizing, and transacting with affiliated DERs (\$); C_i^P is the possible penalty cost if the service failure or against the rules of contract (\$); C_i^{Au} is the uncertainty cost according to communication, policies, enforcement, etc. (\$); and Q_i^{Agg} is the maximum production of active or reactive energy (kWh)/(kVarh).

Herein, P_N^{Agg} is the last accepted block and its marginal price, P_{N+1}^{Agg} is the first rejected offer, the uniform price for clearing is then set equal to P_N^{Agg} . Note that, the selection of P_N^{Agg} should firstly meet the DSO willing price $P_{Con,max}^{DSO}$ (the red dotted line), i.e. $P_N^{Agg} \leq P_{Con,max}^{DSO}$. This willing price is

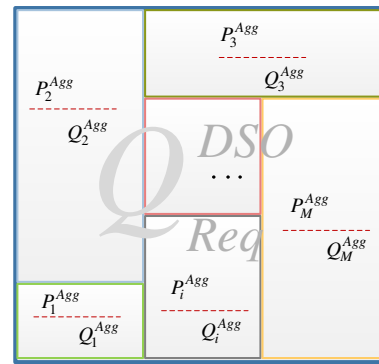


Fig. 4 Super market (SM)

applicable to all categories of flexibility services, could be computed by

$$P_{Con,max}^{DSO} = (C_{Con}^I + C_{Con}^L + C_{Con}^O + C_{Con}^{Du}) / Q_{Con}^{DSO} \tag{2}$$

where, for dealing with the congestions in the whole range of distribution grid, $P_{Con,max}^{DSO}$ is the highest price for DSO willing to pay (\$/kWh)/(\$/kVarh); C_{Con}^I is the investment cost by updating new feeders, substations or Var devices (\$); C_{Con}^L is the load curtailment cost (\$); C_{Con}^O is the operation cost for re-dispatching and grid losses (\$); C_{Con}^{Du} is the uncertainty cost according to communication, policies, transactions, etc. (\$); and Q_{Con}^{DSO} is the maximum requirement of active power or reactive power in this distribution grid (kWh)/(kVarh).

2) Super market (SM): In opposite to the SAA auctions, the aggregators have the initiative in SM setup. Considering the historical data, the aggregators will be able to estimate where and how much the DSO might be interested in purchasing the desired flexibility services. Then, the aggregators could propose and price various services, just like in the “super market”, the DSO is the consumer of these flexibility services willing to choose their favourite commodities.

Furthermore, this SM trading setup could be formulated by a portfolio optimization problem [11], as indicated in Fig. 4. Q_{Req}^{Agg} is the total required active or reactive energy of DSO (kWh)/(kVarh). The expected value of DSO willing price (i.e. clearing price) can be expressed as the weighted average of the individual expected price of each aggregator,

$$P_{Exc}^{DSO} = \sum_{i=1}^K P_i^{Agg} \omega_i \tag{3}$$

$$\omega_i = Q_i^{Agg} / Q_{Req}^{DSO} \tag{4}$$

where, for a type of flexibility service to deal with the congestions in the whole range of distribution grid, P_{Exc}^{DSO} is the DSO expected price (\$/kWh)/(\$/kVarh); K is the total

number of the aggregators to participating in SM; for i th aggregator, P_i^{Agg} is the expected price (\$/kWh)/(\$/kVarh); ω_i is the share in this portfolio (%); Q_i^{Agg} is the production of active or reactive energy (kWh)/(kVarh).

Subsequently, the optimal value of ω_i can be calculated by an optimization problem with the objective of minimizing the DSO portfolio investment risk, denoted as σ_p and described as

$$\text{Min } \sigma_p = \left[\sum_{i=1}^K \sum_{j=1}^K \omega_i \omega_j \sigma_i \sigma_j \rho_{ij} \right]^{1/2} \quad (5)$$

$$\text{s.t. } \sum_{i=1}^K \omega_i = 1 \quad (6)$$

$$0 \leq \omega_i \leq \omega_{i,\max} \quad (7)$$

$$\omega_{i,\max} = Q_{i,\max}^{Agg} / Q_{Req}^{DSO} \quad (8)$$

$$\rho_{ij} = 1, \quad \text{if } \omega_i = \omega_j \quad (9)$$

where (6)–(9) are the constraints of proportional allocation of individual aggregator in this portfolio. For i th aggregator, $Q_{i,\max}^{Agg}$ is the maximum output of this type of flexibility service, $\omega_{i,\max}$ is the upper limit of the proportion in this portfolio. σ_i and σ_j are the standard deviations corresponding to the holding period returns of annual costs of

the i th and j th aggregators, respectively, and ρ_{ij} is the correlation among them.

These two trading setups do not necessarily replace each other, but will be a mutually beneficial co-existence according to their own merits.

3.2 Trading processes

1) SAA-based trading process:

The SAA-based trading processes in FLECH are shown in Fig. 5 and depicted below:

- DSO planning: during the DSO year-ahead planning and scenario analysis, the requirement of flexibility services can be identified, including service category, area, location, quantity, and activation numbers.
- DSO-aggregators contracting: the DSO posts the desired flexibility services at FLECH with a deadline for aggregators to submit offers. Then FLECH announces this information on the website. Accordingly, aggregators will pre-schedule the affiliated DERs and submit flexibility service offers to FLECH with explicit quantity, price and maximum activation numbers. DSO gets the area merit order list and assesses the feasibility of various offers based on OPF. By trading off the grid reinforcement or flexibility service purchase by (2), if DSO could see the substantial benefits in mobilizing flexibility services, the desirable offers will be taken and standard contracts will be made.
- Flexibility services activation: when the contractual service period is coming, the DSO will activate flexibility services as specified in the contract, if necessary. Aggregators will schedule, optimize and coordinate DERs refer to contracted flexibility services.
- Flexibility services verification: till the contractual service period is over, a bilateral verification between DSO and aggregators will be carried out to authorize the exactly delivered flexibility services.
- Settlement: according to the authorized flexibility services, settlement between the DSO and involved aggregators will be accomplished, simultaneously, the mutual contractual obligations have been fulfilled.

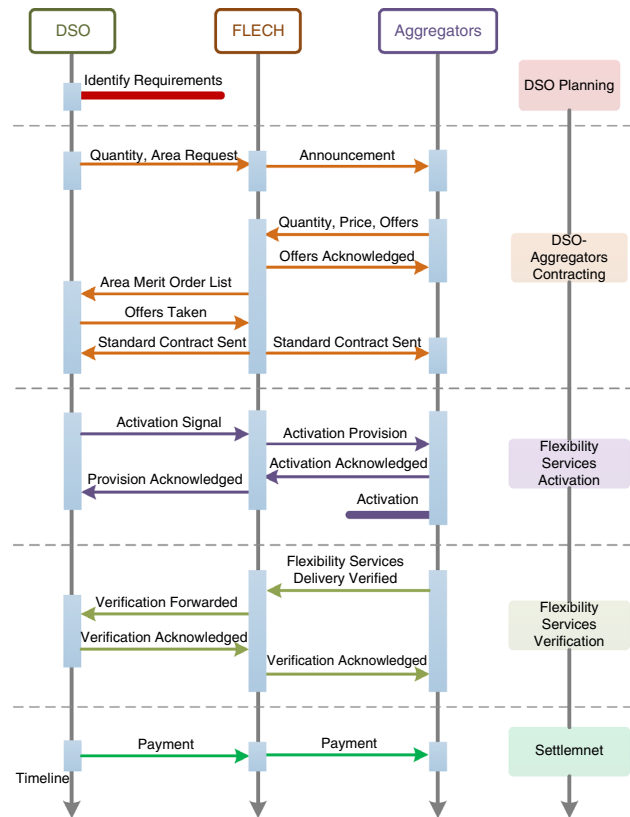


Fig. 5 SAA-based trading processes in FLECH [12]

2) SM-based trading process:

The processes of SM-based trading in FLECH are similar with SAA-based trading procedures in flexibility services activation, verification, and settlement, but differ over the first two processes, as illustrated in Fig. 6.



- **Aggregator forecasting:** on basis of the historical data, the aggregators will forecast the DSO favourite flexibility services in prior day/month and identify the productions by pre-scheduling the affiliated DERs.
- **DSO-aggregators contracting:** the aggregators submit the flexibility services bids to FLECH with service category, area, location, quantity, price and maximum activation numbers. FLECH will announce the bids information on the website after acknowledgement. Then the DSO will make flexibility services portfolio optimization adapted to his willing price refer to (3)–(9). Whereby, the preferred bids are taken, the DSO will stipulate the types of flexibility services and sign standard contracts with aggregators in FLECH.

the backbone. Therefore, the stipulated flexibility services due to different congestion management categories are elaborated in this section.

4.1 Overload management

For satisfying DSO requests of feeder overload management, five types of flexibility services feasibly provided by aggregators are defined as FS_{OP} , FS_{OU} , FS_{OR} , FS_{OC} and FS_{OM} . The expected service effectiveness for individual flexibility service is shown in solid orange line in Fig. 7, additionally, the desired quantity of each service for eliminating peak load, i.e. Q_{FSOP} , Q_{FSOU} , Q_{FSOR} , Q_{FSOC} and Q_{FSOM} , is also shown in the shaded area, respectively.

4 Flexibility services

As mentioned above, aiming to explore FLECH market solution to relieve the congestions in distribution grid, contractual flexibility services offered by aggregators are

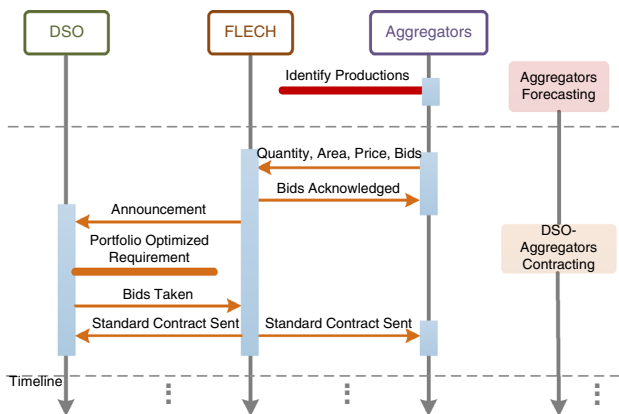


Fig. 6 First two sections of SM-based trading processes in FLECH

- FS_{OP} is suitable for handling the predictable peak loads for periodically daily capacity issues, if the distributions grid experiences the highest load and the hourly load patterns could be forecasted at each feeder, then the DSO will desire the load reduction service from aggregators hourly. This service will ensure the whole overload situation under 70 % capacity limit, previously activated before the load touching this limit and terminated later than the overload gone, shown in Fig. 7a.
- FS_{OU} is an event-based flexibility service, which looks similar to FS_{OP} but will be activated sharply when overload starts, shown in Fig. 7b. This service will be less frequently activated every day during contractual period.
- FS_{OR} has the ability of exploiting the new reserve-supply within the feeder capacity limit of 70 %–100 %. Moreover, in view of un-locking this expansion of available capacity, it is necessary to reduce loads when facing such a situation. However, this type of flexibility service will be rarely activated as it will only be served when a neighbouring feeder get faulted plus the load

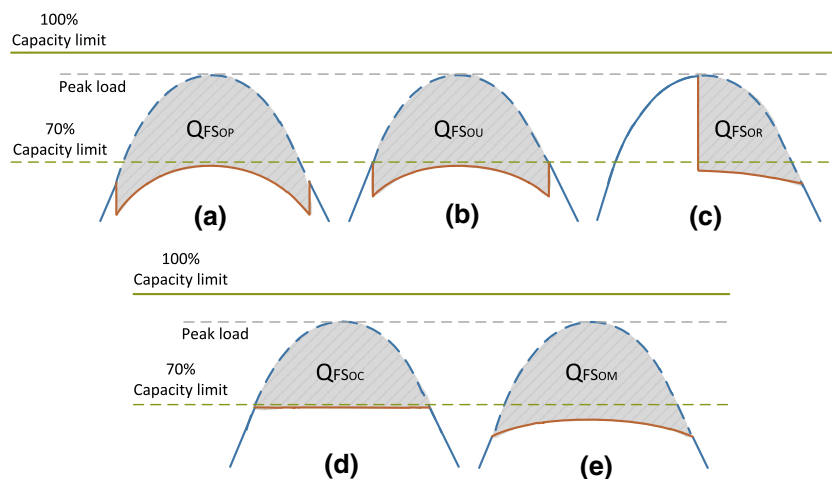


Fig. 7 Flexibility services offered by aggregators for overload management. **a** FS_{OP} . **b** FS_{OU} . **c** FS_{OR} . **d** FS_{OC} . **e** FS_{OM}

Table 2 Quantitative sample of flexibility services

Service	FS _{OP}	FS _{OU}	FS _{OR}	FS _{OC}	FS _{OM}	FS _{VS}	FS _{VV}
1 Contract valid	Dec. 1–31	Dec. 1–31	Dec. 1–31	Dec. 1–31	Dec. 1–31	Jan. 1–31	Jan. 1–31
2 Area-location	240–24791	270–27791	420–46791	310–34891	324–324791	261–265891	108–189125
3 Activation-time	–	15 min	5 min	10 min	–	5 min	5 min
4 Activation-duration	4 h	3 h	3 h	3 h	4 h	2 h	2 h
5 Activation-quantity	200 kWh	–	–	–	200 kWh	250 kVarh	500 kVarh
6 Activation-number	20	15	1	10	20	30	18
7 Price	3 \$/kWh	10 \$/kWh	6 \$/kWh	4 \$/kWh	3 \$/kWh	2 \$/kVarh	1 \$/kVarh
8 Failure-penalty	4 \$/kWh	15 \$/kWh	8 \$/kWh	5 \$/kWh	4 \$/kWh	4 \$/kVarh	2 \$/kVarh

exceeding the 70 % capacity limit during the exactly hours of a year. Once this situation occurs, DSO can open the spare capacity of this feeder as a reserve to keep an adequate supply. In case the surge beyond the 100 % capacity limit, FS_{OR} service should be activated timely to hold the peak load back under 70 % capacity limit, as shown in Fig. 7c.

- FS_{OC} pledges a feeder capacity limit specified by the DSO will not be violated, see the flat solid orange line nearly 70 % in Fig. 7d.
- FS_{OM} means that the aggregators have the obligation to guarantee their local portfolio will not exceed a certain quantity which identified by DSO, as shown in Fig. 7e.

4.2 Voltage management

For serving the DSO with voltage stability support, there are two flexibility services can be offered to ensure that the respective feeders stay within a proper voltage band (e.g. ± 10 %).

- FS_{VS} will be specified by DSO in different voltage levels with the best knowledge of grid state, and the contracted aggregators have to ensure these voltages will not beyond the limits.
- FS_{VV} mobilizes the aggregators to cooperate with the reactive power control of DSO, primarily for the voltage of transformers maintained in the particular limits.

4.3 Quantitative example

For each flexibility service, a set of contractual prerequisites should be explicitly stipulated to achieve an efficient and economic operation, including service price, area, location, duration, activations, failure and penalty

statement, etc. Certain feeders in a 10 kV distribution grid are taken for a sample to further illustrate the stipulations of these services, shown in Table 2.

5 Conclusion

A FLECH market is proposed to deal with the rising requirements of DSO congestion management. The parallel running structure with existing market makes it possible to perform their duties, namely, eliminate the congestions in distribution grid and circumvent imbalances in transmission grid, respectively. Furthermore, the SAA and SM trading setups and processes of FLECH market are analyzed exhaustively. In addition, the typically defined flexibility services, i.e. FS_{OP}, FS_{OU}, FS_{OR}, FS_{OC}, FS_{OM}, FS_{VS} and FS_{VV}, are categorized and described comprehensively with a quantitative sample. The proposed FLECH market shows its superiority to benefit DER owners and facilitate DSO dispatch and operation, which will contribute to improve the stability and reliability of distribution grid even transmission grid.

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References

- [1] Omu A, Choudhary R, Boies A (2013) Distributed energy resource system optimisation using mixed integer linear programming. *Energ Policy* 61:249–266



- [2] Ding Y, Pineda S, Nyeng P et al (2013) Real-time market concept architecture for EcoGrid EU—A prototype for European smart grids. *IEEE Trans Smart Grid* 4(4):2006–2016
- [3] Hansen H, Hansen LH, Johannsson H et al (2013) Coordination of system needs and provision of services. In: *Proceedings of the 22nd international conference and exhibition on electricity distribution (CIRED'13)*, Stockholm, Sweden, 10–13 Jun 2013, 4 pp
- [4] Romanovsky G, Xydis G, Mutale J (2011) Participation of smaller size renewable generation in the electricity market trade in UK: Analyses and approaches. In: *Proceedings of the 2nd IEEE PES international conference and exhibition on innovative smart grid technologies (ISGT Europe'11)*, Manchester, UK, 5–7 Dec 2011, 5 pp
- [5] O'Connell N, Wu QW, Østergaard J et al (2012) Day-ahead tariffs for the alleviation of distribution grid congestion from electric vehicles. *Electr Power Syst Res* 92:106–114
- [6] Danish climate and energy policy. Danish Energy Agency, 2012
- [7] Glatvitsch H, Alvarado F (1998) Management of multiple congested conditions in unbundled operation of a power system. *IEEE Trans Power Syst* 13(3):1013–1019
- [8] Kiény C, Berseneff B, Hadsaid N et al (2009) On the concept and the interest of virtual power plant: Some results from the European project Fenix. In: *Proceedings of the IEEE Power and Energy Society general meeting (PES'09)*, Calgary, Canada, 26–30 Jul 2009, 6 pp
- [9] Mashhour E, Moghaddas-Tafreshi SM (2011) Bidding strategy of virtual power plant for participating in energy and spinning reserve markets—Part I: problem formulation. *IEEE Trans Power Syst* 26(2):949–956
- [10] Peik-Herfeh M, Seifi H, Sheikh-El-Eslami MK (2013) Decision making of a virtual power plant under uncertainties for bidding in a day-ahead market using point estimate method. *Int J Electr Power Energ Syst* 44(1):88–98
- [11] Fang Y, Lai KK, Wang S (2008) *Fuzzy portfolio optimization: theory and methods*. Springer, Berlin
- [12] Nordentoft NC, Ding Y, Zhang CY et al (2013) Development of a DSO market. Final Report of iPower project WP3.8, Copenhagen, Denmark
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