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AGGREGATION OF HETEROGENEOUS FLEXIBILITY RESOURCES PROVIDING SERVICES FOR SYSTEM OPERATORS AND THE MARKET PARTICIPANTS

ISTVÁN BALÁZS *[1], ATTILA FODOR[1], AND ATTILA MAGYAR[1]

[1]Department of Electrical Engineering and Information Systems, Faculty of Information Technology, University of Pannonia, Egyetem u. 10, Veszprém, 8200, HUNGARY

Power systems characterized by large, centralized generation sources and the typical flow of energy from the transmission grid to the distribution grid towards consumers are evolving. The increasing penetration of intermittent and distributed renewable energy generation is forcing system operators to increase the volume of balancing capabilities and procure flexibility services at the distribution grid level that must be supported by the aggregation of small-scale resources connected at the distribution grid. This paper suggests an aggregator framework that provides services for both operators of transmission and distribution systems while optimizes its portfolio to perform on wholesale energy trading markets too. Overlaying phases of multi-period optimization runs are proposed that incorporate stochastic renewable energy generation as well as load forecasts and, moreover, the continuously changing business context while enabling cooperation between optimization phases throughout the business process.

Keywords: generation aggregator, optimization, distributed energy resources, TSO-DSO coordination, smart grid

1. Introduction

Conventional power systems are characterized by large generation sources that inject power into the transmission grid, which is transported to distribution networks before being delivered to the end users. Power flows one way from the high-voltage transmission grid to the end user at low-voltage networks. Centralized, dispatchable and predictable generation provides flexibility at the transmission level to the electricity system to balance generation and demand.

The increasing amount of distributed and renewable generation (from around 21% of total net electricity generation in 2010 to 44% in 2030 [1]) has transformed generation into a more variable and intermittent source of energy. Demand has become more active, emphasizing the engagement of consumers. Distributed generation (DG), demand response (DR) and storage facilities will become important components of power systems in the future. These resources are connected to low- and medium-voltage networks, thus, making the distribution grid a crucial element of the electricity sector.

The increasing penetration of intermittent generation and distributed energy resources has already forced TSOs (Transmission System Operator) to increase the volume of balancing capabilities and start procuring services for system balancing not only from the transmission grids but also from distribution grids. An important concept is flexibility, that is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation), in order to provide a service within the energy system [2]. It is the active management of an asset that can impact the balance of a system or power flows to the grid on a short-term basis. The proper management of available flexibility, both in terms of generation and demand, can help to compensate for the lack of certainty with regard to renewable sources.

On the other hand, DSOs (Distribution System Operator) have started to manage congestion actively in their distribution grids and consider procurement of flexibility services to redispatch the system at the distribution level. As a result, the same flexibility resources could also be potentially used for congestion management and voltage control by the TSO and DSO [3]. Conflicts of interest may arise between the TSO and DSO that must be managed by suitable coordination schemes [4], but this also provides an opportunity for players on the distribution grids to offer flexibility capabilities to multiple customers resulting in higher demand.

An aggregator, that is a new market agent, will play a central role in collecting resources on the distribution grid and involving them in markets that are unavailable for them individually. USEF (Universal Smart Energy

*Correspondence: balazsistvan08@protonmail.com

Framework) Foundation's Aggregator Workstream analyzed the different topics related to the role of the aggregator whilst paying particular attention to demand-response aggregation as well as the relationship between an aggregator and the BRP (Balance Responsible Party)/supplier. Seven different models to implement aggregation were identified, and advantages as well as limitations evaluated [5]. Flexibility resources were investigated in detail and an information model set up by SmartNet D1.2 [6] that contains a mathematical description of the dynamic behaviour of the resource, its constraints in terms of flexibility provision, and a formulation of the different components of costs needed to provide flexibility. The research project BestRES (Best practices and implementation of innovative business models for Renewable Energies aggregators) [7] explored different ways in which an aggregator can create value, and categorized services that are provided into internal (own balancing) as well as external reasons (wholesale, retail, reserve capacity mechanisms).

An aggregation function manages distributed energy resources, the optimization of dispatch by taking into consideration the states of a time-variant system is a core capability. With regard to isolated microgrids, Olivares et al. [8] proposes a stochastic-predictive control approach. The uncertainty of an isolated grid for a single purpose (generation and load balancing) is addressed, a two-stage stochastic receding horizon approach is presented that can be generalized to develop formulations for market-connected multi-purpose optimization scenarios.

The objective of this study is to develop a framework for an aggregator that implements the aggregator role of heterogeneous distributed energy resource management, complies with the typical electricity market model, follows its business processes, and operates in both wholesale energy and electricity balancing markets.

The present paper provides novelties in terms of aggregator roles. It is based on a centralized approach where a new market agent, the aggregator, manages the flexibilities of a portfolio and offers services to TSO, DSO and external BRPs. In addition, it participates in wholesale energy trading activities and co-optimizes resource portfolios for both energy trading as well as flexibility services. The building blocks of such an aggregator have been determined: 3 phases of an overlaying optimization process are recommended, optimization requirements are defined and input/output parameters determined to enable cooperation between optimization phases throughout the business process.

Section 1 introduced challenges that concern the energy sector, defined a problem statement and presented current research as well as implementations. Section 2 describes the architecture of an aggregator extending the virtual power plant concept with heterogeneous resources of flexibility and the optimization module. Differences between typical aggregator definitions and functions proposed in this paper are highlighted. An architecture is planned where optimization is separated from the generator control module as it has to solve a much more complex problem than regular, built-in dispatch functions face. The business context is presented that assumes a complex optimization approach as introduced in Section 3. Here optimization requirements are collected to fulfil the objectives of previous sections and to optimize process phases, data exchange between phases is determined.

2. Aggregator framework

The flexibility center (FC) is introduced in this paper as an entity that implements the role of the aggregator. It is a framework of tools and functions that enable the aggregation of distributed, heterogeneous flexibility resources and provide services in wholesale markets. Components of the FC will be presented as well as its operating environment in order to provide a framework for optimization of heterogeneous energy resources.

2.1 Aggregator role

According to the definition derived from the Universal Smart Energy Framework (USEF) [9], an aggregator is responsible for acquiring flexibility from prosumers, aggregating it into a portfolio, creating services that draw on the accumulated flexibility, and offering these flexibility services to different markets that serve various market players. In return, the aggregator receives the value it creates on these markets and shares it with the prosumer as an incentive to shift its load. In the definition above, USEF only restricts the scope of the aggregator for prosumers by limiting the activities of the aggregator with regard to demand response aggregation. The EU Commission proposal for the recast of the E-Directive [2] defines the aggregator as a market participant that combines multiple customer loads or generated electricity for sale, purchase or auction in any organised energy market. In this study the Commission's definition is used that incorporates aggregation of all types of decentralized energy resources.

The objective of the research is to identify optimization use cases of an aggregator, so assumptions have to be made to simplify the market environment the aggregator operates in. To be able to ignore challenges concerning the dissociation of energy supply / wholesale energy trading and flexibility activation, which is a significant change to current market models, the FC implements the role of the aggregator using an integrated aggregator model [5]. Following the integrated model, the roles of the supplier/trader and aggregator are combined into one market party, both of which are part of the same balancing group, contracted by the same BRP. Since compensation for imbalances and the open supply position are unnecessary, portfolio optimization efforts rather than market issues remain the primary focus.

Definitions and implementations of an aggregator, as referenced in Section 1, outline a model aggregator as a service provider that responds to external requirements. In this study, the role of the aggregator is extended to operate on the wholesale energy markets as well, in cooperation with its BRP/energy trader. It is proposed that the Flexibility Center should both fulfil external requests and participate in energy trading to optimize economic gain.

2.2 Architecture

The proposed Flexibility Center contains individual modules that cooperate to implement the roles of aggregation.

The SCADA (Supervisory Control and Data Acquisition) system is responsible for data acquisition and control. It can be considered as a low-level interface to the controlled resources. Standard building block.

The AGLC (Automatic Generator Loading Control) module controls power levels concerning elements of the portfolio using SCADA services based on the expected optimized dispatch. Standard building block.

The forecast module provides forecasts with regard to generation, consumption volumes and market prices. Generation and consumption is forecast as a standard function for any implementations that control intermittent resources. However, price forecasting is an additional function required by the trading responsibility of the Flexibility Center.

The proposed architecture of the aggregator defines optimization as an individual module. According to the proposed architecture, it has an extended responsibility, enabling the Flexibility Center to control a diverse portfolio of distributed resources and optimize their capacities in order to both participate in wholesale energy markets and fulfil external requests for flexibility activation.

2.3 Services offered and customers

The Flexibility Center provides services for its customers in terms of aggregating the flexibility capabilities of distributed resources. In terms of the FC, the reason why a customer requested flexibility is irrelevant. However, to prepare high-quality services that meet the technical requirements of the customer and are profitable for the FC, a set of offered services has to be defined. Fig. 1 presents connections between flexibility providers, the Flexibility Center and customers. The Flexibility Center provides services to potential customers:

Internal BRP: FC provides optimal dispatch of the portfolio and trading recommendations to maximize profit on the day-ahead and intraday energy markets. FC can use the portfolio of its own balancing group to minimize imbalance costs of providing such a service for the balance responsible party (BRP) of the balancing group near the delivery time.

TSO: TSO procures balancing reserves to ensure resources for load-frequency control. FC can bid on both balancing capacity and balancing the energy market by offering frequency restoration reserves (FRR).

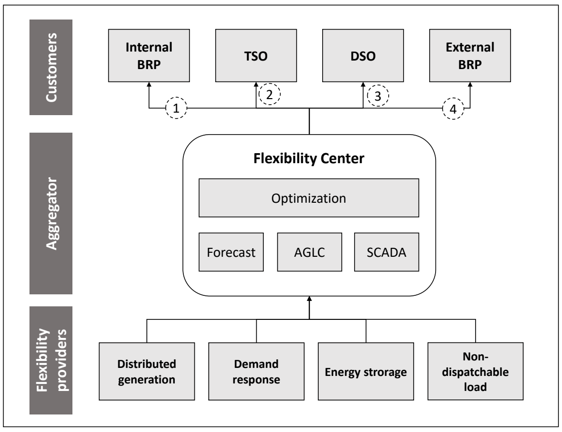

Figure 1: Flexibility Center services and operational context

DSO: DSO's will be empowered to actively purchase local flexibility capabilities to mitigate voltage and grid congestion problems due to the increasing penetration of intermittent and distributed energy resources in the distribution system. FC can bid on future local flexibility markets by offering services for congestion management in the distribution network [9]. Voltage / reactive power controls may also be a positive use case, but these are not considered in this study.

External BRP: Similarly to the internal BRP service, it is also economically worthwhile to balance an external BRP portfolio [10].

2.4 Flexibility resources

Distributed generation refers to power generation facilities connected to the distribution grid. It may consist of predictable, dispatchable and intermittent generation. Demand response is defined as the changes in energy use by end users (domestic and industrial) from their current/normal consumption patterns in response to market signals. Energy storage can be used to store an excess of energy during high generation periods and transform it back into electricity during periods of high demand or to balance the power system. A non-dispatchable load is the consumption of an end user that does not participate in demand response programs.

3. Optimization phases

Markets, in which the FC operates, change over time during the same delivery period. Information on the market, assets of the portfolio, contractual commitments and weather conditions all change over time and the FC optimization function has to reflect such changes. An optimization approach is proposed that takes into consideration the changing objectives and status of the optimization phases.

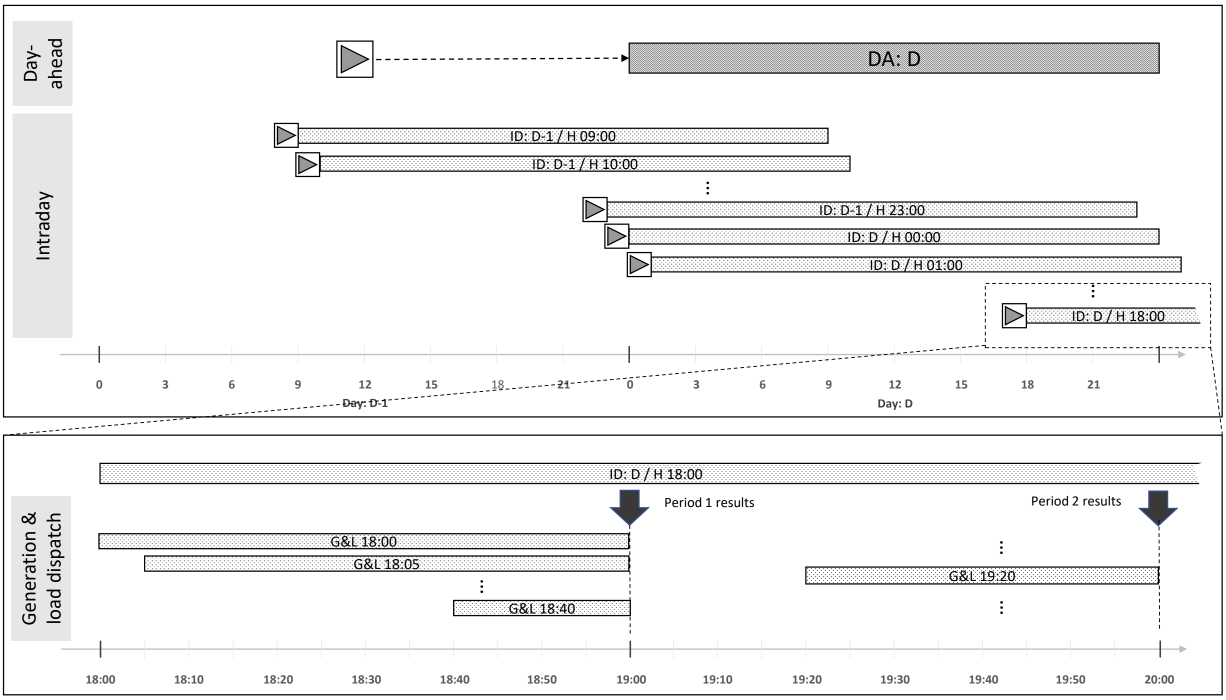

Figure 2: Examples of optimization phases and look-ahead windows

3 phases are identified that are built upon each other. Each phase shares the same primary objective to maximize profit, but the objective function, set of variables, parameters and constraints may differ as the time of delivery approaches and former calculations/forecasts become reality. In order to prepare a consistent optimization framework for the FC, optimization phases are identified and descriptions provided.

Fig. 2 depicts an example of overlaying optimization runs. Day-ahead planning is run once a day, intraday planning is initiated every hour, and Generation and load dispatch is executed every 5 minutes. Once initiated, all optimization runs have to update optimization parameters so they can provide progressively more precise results.

3.1 Requirements of optimization

Requirements of wholesale energy and flexibility activation call for a complex optimization approach. In this paper, common optimization requirements are identified, however, detailed formulations will be developed as part of future research.

The Flexibility Center as an aggregator manages distributed resources that use the grid but does not operate the grid. It is not responsible for nor able to perform network monitoring and control, thus, the grid is not modeled, rather an economic dispatch problem is solved by FC optimization. Due to uncertainties concerning consumption and intermittent renewable generation, a stochastic optimization function has to manage multiple, probability-weighted load and generation scenarios. Energy storage, ramping and unit commitment considerations require a multi-period planning horizon.

Objective functions are formulated to maximize profit and optimization phases share execution results, but they all solve a different optimization problem. Variables, parameters, cost functions and constraints must be aligned accordingly.

Contractual commitments have no cancellation value, these are obligatory constraints. Orders from contracted customers (TSO, DSO, BRP) must be superposed to fulfil expectations and incorporated into the portfolio optimization model.

3.2 Day-ahead planning

The goal of the day-ahead planning phase is to provide portfolio dispatch for schedule nominations containing make-or-buy recommendations based on market price forecasts. Since this is performed on a daily basis, the run time is not critical. Multi-stage stochastic unit commitment and economic dispatch optimization are recommended to mitigate generation and load uncertainties. Periods of 15 minutes in duration are necessary to meet the requirements of the nomination process.

Input parameters for day-ahead planning are reserved flexibility capacities, contractual commitments (e.g. reserved capacities, commercial contracts), the state of the system at the beginning of day D according to the previous intraday run, technical and price parameters with regard to the assets of the portfolio, the generation forecast of intermittent resources, the consumption forecast of loads, and the day-ahead spot price forecast. The out-

Table 1: Timeframes of phases

Phase	Interval	Number of runs	Periods
DA	1 calendar day	1 / day	96×15 min periods
ID	24 hours	24 / day	96×15 min periods
G&L	$60-5$ mins	12 / hour	$12-1 \times 5$ min periods

put contains the power dispatch of the portfolio including binary unit commitment decisions and day-ahead trading recommendations.

Table 1 summarizes optimization intervals and the duration of each phase. The results of day-ahead optimization are inputted into schedule nominations and day-ahead trading so a calendar day is covered but executed according to nomination schedules from the middle of the previous day.

3.3 Intraday operation

The primary objective of the intraday run is to determine the system state at the end of the first hour which is then used by generation and load dispatch as a target state (19:00 according to the example in Fig. 2). It can also be used to fine-tune day-ahead results and produce inputs for intraday trading and schedule modifications.

Intraday optimization takes into consideration unit commitment decisions, nominated day-ahead as well as intraday schedules, reserved capacities, more precise weather as well as price forecasts, portfolio parameters and the current state of the system provided by the SCADA module, price parameters of the assets from the portfolio, and activation orders from customers. It is executed hourly by applying a 24-hour look-ahead window. The run-time is critical and the unit commitment is not revised, but probability-weighted generation and load scenarios still need to be generated for stochastic optimization. Multi-period stochastic optimization is recommended. The duration of periods is 15 minutes to support intraday trading.

3.4 Direct generation and load dispatch

Intraday optimization performs a 24-hour run and determines a target system state for a direct generation and load dispatch run to calculate optimized dispatch for the Automatic Generator Loading Control module. Here the optimization interval is 1 hour and the duration of calculations is 5 minutes. The result of the first period is used by the AGLC to directly control the assets of the portfolio.

The initial parameter set is the actual system state provided by the SCADA module, the target state is determined by the intraday run. It also follows the shrinking horizon model by being executed every 5 minutes and performing calculations up until the hourly target. Results must be sent to AGLC to control assets since the run-time is extremely critical. A deterministic optimization linear programming formulation is proposed.

4. Conclusion

In this paper, an aggregator framework was presented that aims to manage distributed energy resources, provide services for system operators, support BRPs to minimize imbalances in the balancing group, and determine energy trading volumes in day-ahead and intraday markets. 3 phases of overlaying process optimization were recommended in line with a regular marketing process.

A. Appendix: Acronyms

Abbr.	Description
AGLC	Automatic Generator Loading Control
BRP	Balance Responsible Party
BSP	Balancing Service Provider
DG	Distributed Generation
DR	Demand Response
DSO	Distribution System Operator
FC	Flexibility Center
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator

B. Appendix: Definitions

Balancing Group: a group of market participants (consumers, producers, traders) who optimize costs by netting deviations (imbalances) and reduce overall deviations between the projected and reported electricity usage.

Balance Responsible Party: a chosen representative of a balancing group who is responsible for the imbalance of the group.

Balancing Service Provider: a market participant providing balancing services to the TSO.

Balancing Services: (1) balancing energy is energy used by TSO to perform balancing and (2) balancing capacity, namely a volume of capacity that a BSP has agreed to hold to and in respect of to which the BSP has agreed to submit bids for a corresponding volume of balancing energy to the TSO.

Balancing: balancing encompasses all actions and processes through which TSO ensures the system frequency is within a predefined stability range and complies with the amount of reserves needed with respect to the required quality.

Distribution System Operator: responsible for providing and operating low-, medium- and high-voltage networks for the regional distribution of electricity as well as for the supply of lower-level distribution systems and directly connected customers.

Transmission System Operator: responsible for providing and operating high- and extra high-voltage networks for the long-distance transmission of electricity as well as for the supply of lower-level regional distribution systems and directly connected customers.

Prosumer / active customer: customers who consume, store or sell electricity generated on their premises, or participate in demand response or energy efficiency schemes provided that these activities do not constitute their primary commercial or professional activity.

Demand response: the change of electricity load by final customers from their normal or current consumption patterns in response to market signals, including time-variable electricity prices or incentive payments, or in response to acceptance of the final customer's bid.

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