Use case description of real-time control of microgrid flexibility

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***Abstract*—Increasing amount of distributed energy resources necessitates more flexibility at the distribution network level. One option to attain this flexibility is by aggregation of these resources within microgrids and further supervisory control of the latter in active network management. Among other reasons preventing their realization, these flexibility services lack standardized information and communication technology solution. This study assesses the required communication, information, and functional competences for such services and describes them by means of a use case modeling on smart grid architecture model planes. Specifically, the paper focuses on an information exchange built on the basis of web application programming interface called Smart API. The results of the study present a smart grid architecture that would enable real-time control of microgrid resources in active network management through flexibility market services.**

***Index Terms*—microgrid flexibility, real-time control, flexibility services, information exchange interface, smart grid architecture**

I. INTRODUCTION

It is generally assumed that the next paradigm shift of distribution system operators (DSO) management will be linked with the services of real-time supervision of distributed energy resources (DER) and their interactions with upstream networks and markets [1], [2]. Moreover, further development of information and communication technologies (ICT) and potential energy market regulation may enable DSOs to use customer DERs for active network management (ANM) as a low-cost alternative to traditional management measures [3]. The efficiency of such an approach is found in the ability of these supply- and demand-based DERs to provide flexibility to grid operation by altering generation or consumption patterns in reaction to external signals [4].

In the literature, different methods to connect these flexibility resources to management of the grid through the operational market services are currently the object of much study. The underlying principle of much of this research can be summarized by the concept of flexibility service markets that represent a platform for activating flexibility trading and coordination between customers, market actors and grid operators [5], [6], [7]. One of the main functions of the platform is to improve information exchange about distribution network capacity within different time-frames between all actors to guarantee optimal operation of the network as a whole and enable new innovative energy services. For instance, the topic of the aggregator selling excessive microgrid reserves on the flexibility service market is undergoing intense study [8], [9]. In such a scalable concept, an aggregated portfolio of grid-connected microgrids with management of multi-energy resources holds huge potential as a source of up- and down-regulated flexibility that can be utilized for diverse balancing and ancillary services [10]. However, most of the research focuses on individual application of this flexibility rather than multi-purpose use of the resources [11], [12]. Moreover, adoption of these services in real-time, which is considered the most demanding feature, has received little attention [13]. Furthermore, a lack of a standardized ICT solution that would enable utilization of flexibility services when required, as well as facilitate situational awareness and concurrency across multiple market actors and markets, is among the many unresolved issues that need further investigation [14].

The aim of this paper is to analyze required communication, information, and functional competencies enabling consistent real-time control of microgrid resources for flexibility services. The outcome of this analysis provides a scalable smart grid architecture for the integration of supply- and demand-side flexibility services into ANM through flexibility service market. In particular, this architecture describes an ICT solution of an information exchange interface that facilitates real-time supervision of microgrid flexibility between the automation systems of flexibility market actors. The ICT solution is based on web application programming interface (API) called Smart API that enables secure and flexible access to the heterogeneous environments found in electricity networks using semantically linked data [15].

The architecture is visualized and examined on the planes of smart grid architecture model (SGAM) in the form of ICT analysis consisting of a functional analysis (SGAM Business and Function layers) and architectural description (SGAM Component, Information, and Communication layers) [16]. The former identifies functional requirements for the realization of a smart grid use case while the latter delivers a technical solution for the implementation of these functionalities.

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II. Functional analysis

A. Business layer

The business analysis establishes business use cases (BUC) that describe the realization of the goals of different stakeholders and that comprise particularly high-level use cases (HLUC). Microgrid flexibility as a market commodity can potentially be utilized on different time scales by a variety of entities for a number of commercial and technical services [17]. This paper focuses on technical use cases that use automatic control of microgrid flexibility within the range of milliseconds to minutes to support normal grid operation in conditions of high DER integration.

The SGAM Business layer, illustrated in Figure 1, includes the following business actors: the aggregator, microgrid operator (MO), prosumer, DSO, transmission system operator (TSO), flexibility market operator (FMO), and service provider (SP). The aggregator aims to maximize his own financial profit by providing a market interface to the microgrid flexibility. The FMO attempts to ensure a market settlement for the offers of the aggregator. The MO carries out the technical part of the procurement of microgrid flexibility by scheduling microgrid resources so, that maximum amount of flexibility can be achieved at every given moment. The MO may provide this resource management service for DER owners (prosumers) that are aiming to reduce their total energy cost by efficiently utilizing flexibility. The SP delivers additional forecast and analysis services to all actors in the flexibility market.

Mutually beneficial cooperation between the above-mentioned actors forms a BUC called Flexibility Services of Microgrids. This BUC is divided into HLUCs called System Balancing and Network Management that describe specific flexibility services for the TSO and DSO, correspondingly. Some of these services are already deployed to some extent in modern grid management and they have led to a reduction in costs [7]. However, most of the applications presented in this work focus on future flexibility services that will become intrinsically viable in conditions of low-carbonized electricity supply. The adoption of the services will depend on many factors including but not limited to the appearance of corresponding regulatory frameworks, remuneration schemes encouraging prosumers to participate in these services over the long-term, the economic feasibility of deployment of these services from the perspective of the DSO and TSO, and the ubiquity of DERs. Moreover, a variety of services and their continuous availability in the flexibility markets will be essential for their widespread distribution since it will encourage grid operators to solve more operational challenges by means of DERs and bring more resources to the market that are only suitable for a limited number of services.

In what follows, possible near real-time flexibility services or HLUCs are presented based on the classification of [17] complemented by material from [18], [19].

1) System Balancing business use cases include opportunities for cost-efficient procurement of reserves via microgrid resources. These opportunities are realized in Frequency Containment Reserve (FCR) use case that utilizes microgrid flexibility to provide the TSO with short-term balancing services to maintain continuous system stability and security. The FCR is described in more detail in [20].

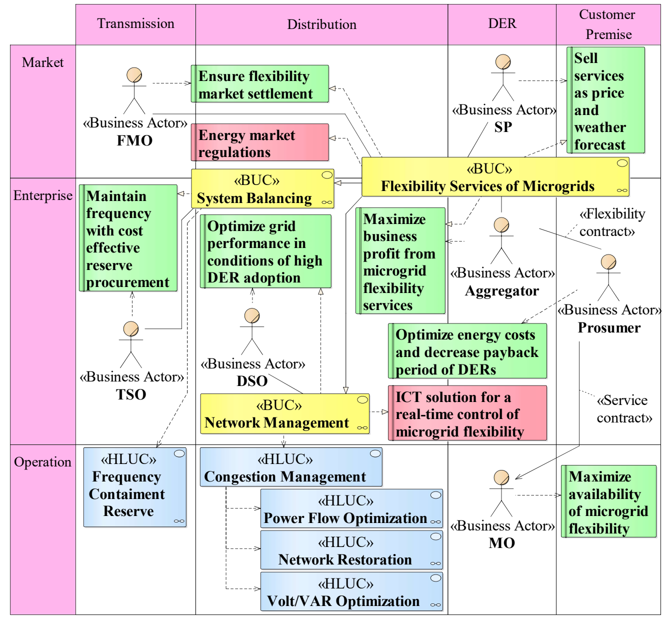

Fig. 1. SGAM Business layer for the Flexibility Services of Microgrids.

2) Network Management business use cases show how the DSO may use microgrid resources to defer or avoid network reinforcements, optimize operational performance, and increase DER hosting capacity while maintaining the service quality and supply security in the network. This BUC is exemplified by Congestion Management HLUC that was highlighted in [19] as a core element of ANM. This HLUC is further decomposed here in the following sub-HLUCs:

- Volt/VAR Optimization – efficient management of voltage profiles and reduction of losses in the network.
- Network Restoration – controlled islanding of the distribution network to reduce the duration of interruptions in power supply in the case of mains failure or blackout as well as congestion services during a restoration phase.
- Power Flow Optimization – reduction of the variation and peak in power flows across the network.

Presented in Figure 1 BUCs impose at least two main requirements for implementation that are the development of corresponding market regulation frameworks and ICT solutions for real-time control of microgrid flexibility. The latter requirement will be examined in next sections.

B. Function layer

The SGAM Function layer aims to specify the minimum functionality needed in the microgrids to provide the above-defined flexibility services. It expands the HLUCs identified in the business layer by decomposing them into primary use cases (PUC). The use of microgrid flexibility as a Conditional Re-Profiling product for congestion management (later on CRP) was chosen as an exemplary HLUC since it describes well the core functionalities that guarantee real-time controllability and observability of microgrid flexibility for logical actors (LA) involved.

The CRP use case, presented as a sequence diagram in Figure 2, shows exchanged general information objects (IO) and can be divided into market and technical processes based on operation time. The market process starts when the MO delivers a flexibility forecast to the aggregator. The latter continuously estimates the aggregated flexibility of all microgrids and, based on the market price forecast, calculates optimal bids in the flexibility market. Meanwhile, if the DSO forecasts a voltage or current congestions, it requests the list of flexibility offers from the FMO. Having checked the technical and economic feasibility of these offers, the DSO purchases some of the offers from the flexibility market. The FMO executes market clearing and sends reserve notification to the aggregators and the DSO. The aggregator then notifies the MO about the purchased flexibility volume, and the MO schedules the resources to guarantee requested amount of the reserves for the specified period of time.

During the technical process the DSO constantly estimates the state of the network in real-time and utilizes optimization algorithms to solve congestions by utilizing microgrid flexibility. As soon as the optimum microgrid flexibility is found, the DSO sends activation commands to the microgrids through the aggregator. Then, MO should spread these commands to microgrid resources and deliver verification of the applied actions to the DSO through the aggregator.

Figure 3 depicts the SGAM functional layer for the technical part of CRP use case with a focus on microgrid functionality that is briefly introduced by the following PUCs:

- Flexibility Forecast – quantifies the flexibility of the microgrid resources during a particular time interval.
- Flexibility Scheduling – schedules the microgrid resources in order to realize network management commands from upper-level automation systems within the operational limits of the microgrid network and the individual DERs.
- Flexibility Verification – verifies the activation of reserved flexibility by comparison of set and activated flexibility.
- Flexibility Acquisition and Control – gathers the measurements from the microgrid resources to coordinate their operation according to the scheduled plan, implement flexibility forecast and verification.
- Data Management – contains the logic of the system operation, handles the data transition and aggregation within the functions of the system, and interacts with a database retrieving, storing, and harmonizing the data.
- Data Acquisition and Transmission – provides an information exchange interface for communication with external actors, processes input data, and translates data models between internal and external standards.

This microgrid functionality can be implemented in both centralized and distributed manner. The former assumes that the MO has access to all the meta-data information about the microgrid resources required to perform the full range of

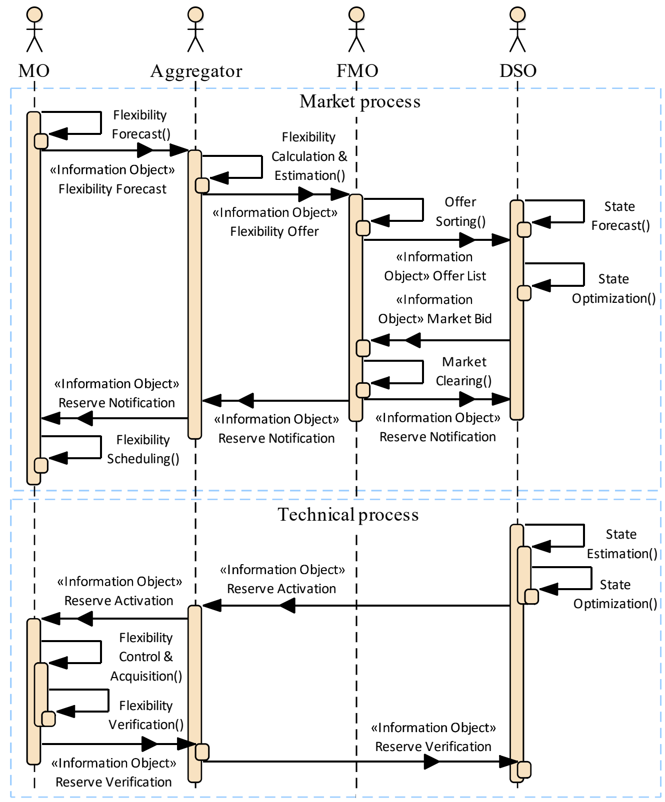

Fig. 2. General sequence diagram of the CRP use case.

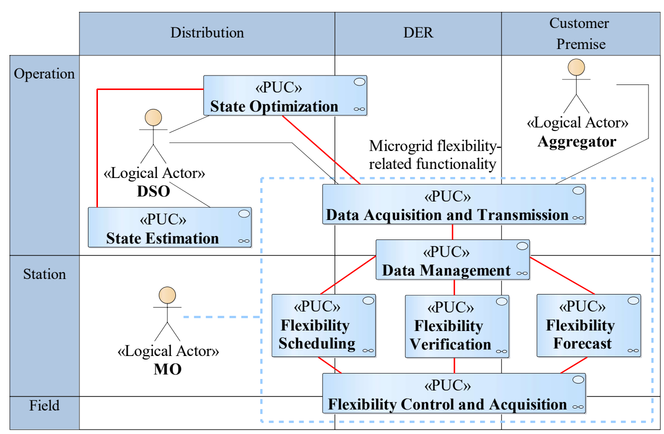

Fig. 3. SGAM Function layer of the CRP use case.

the above-presented functions. Consequently, lower level LAs are only capable of sharing the measurements and executing the control commands of the MO. However, in distributed manner the MO would have only functionality related to data management, acquisition, and transmission, while lower level LAs would perform the flexibility functions on their own.

In Figure 3, the location of the functions reflects the level of the interactions between the LAs. For example, Flexibility Control and Acquisition is the function of the MO that is located in station zone and exerts influence on field devices. This dependence causes position of the function at the intersection of the station and field zones. The same logic is applied to the positions of the other functions.

III. Architectural Description

The ICT architecture of the information exchange interface for microgrid flexibility services is presented in Figure 4 and described in the form of SGAM Information and Communication layers mapped over the Component layer.

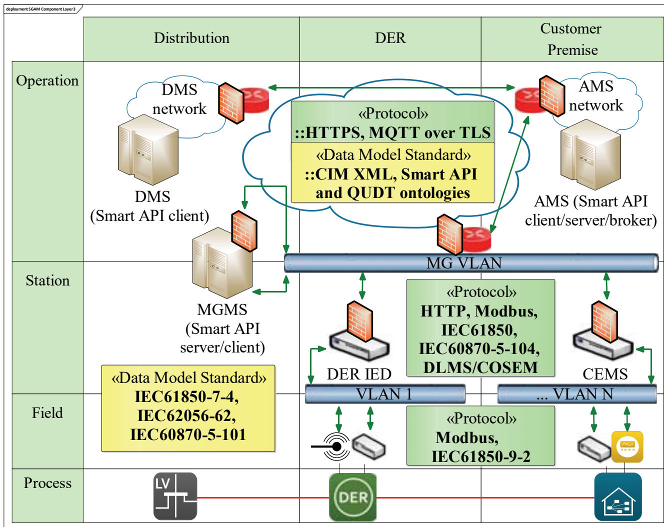

Fig. 4. SGAM architecture view of the CRP use case.

A. Component layer

The SGAM Component layer describes an allocation of previously derived functionalities to hardware devices. The main components of the SGAM layer are aggregator management system (AMS), distribution management system (DMS), and microgrid management system (MGMS).

The network topology of a microgrid can be decomposed into three layers. The lower level of microgrid topology corresponds to the field zone of the SGAM and contains sensors and actuators. These field zone devices sample the data and implement control commands of middle level devices, exemplified in Figure 4 as DER IED (DER intelligent electronic device) and CEMS (customer energy management system). The middle level devices match the station zone of the SGAM and, in practice, they are server-class hardware that may contain time series databases and data acquisition and control logic. Moreover, these devices may contain an embedded energy management system for the implementation of flexibility functions in case of the distributed manner. The MGMS is located at the intersection of station and operation zones and represent the upper level of the microgrid topology. The MGMS is also a server-class hardware and includes all the flexibility service functionalities specified for the MO in Figure 3 above Flexibility Control and Acquisition.

B. Information layer

The SGAM Information layer aims to define the information to be transferred between the MGMS and AMS as well as specify the data models used for this information.

The information on the lower and middle levels of the microgrid topology contains standard data for meter reading and control commands. The data model standards for such data exchange may be extensively used IEC 61850-7-4, IEC 62056-62, and IEC 60870-5-101.

The upper-level exchanges of information are built with linked semantic data sets realized in Smart API that cover concepts from the smart grid domain and can be also used to express measurements. Such data sets may contain quantities, units, dimensions, and data types (QUDT) ontology, Smart API ontology, and a common information model (CIM) with a XML (eXtensible Markup Language) syntax.

The upper-level data exchange of the MGMS includes following general IOs that may group several different messages or actually used in messaging between actors:

- Flexibility Forecast – microgrid report that contains the aggregated *PQ* profile (active and reactive power profile) of the microgrid with limits for possible adjustments during the forecasting time.
- Reserve Notification – submitted bids of the flexibility service market that contain the *PQ* profile specified for the microgrid.
- Reserve Activation – real-time set point for the purchased microgrid *PQ* profile.
- Reserve Verification – microgrid report that reflects the activation of reserved resources and acts as a ground for the payment process.

C. Communication layer

The SGAM Communication layer shows the organization of communication between the microgrid components on different topology layers. On the field level, IEC 61850-9-2 and Modbus protocols that enable interfaces for meter reading and control may possibly be deployed depending on the existing microgrid infrastructure. The corresponding protocols will define the most suitable type of technology for the communication network between the field zone devices and station zone devices. Local area networks (LAN), virtual LAN (VLAN), open virtual private networks (openVPN), and many other technologies may be used for this purpose. As an example, private VLANs with restricted public network access are presented in Figure 4.

In addition to the protocols of the field layer, the communication of the middle layer devices within the station zone may be also built with the use of such protocols as IEC 60870-5-105 and DLMS (device language message specification)/COSEM (COmpanion Specification for Energy Metering) as it is illustrated in the Figure 4. Moreover, hypertext transfer protocol (HTTP) can be used for CEMS. The interactions within the station layer are organized as cycled requests of the client (MGMS) to servers (DER IEDs and CEMSs) through the microgrid VLAN (MG VLAN).

A similar approach with a more secure version of HTTP, i.e. HTTP Secure (HTTPS) over the semantic Smart API, is proposed for communications within the upper level. The use of HTTPS is motivated by the need to secure the data within the public network and MG VLAN, which has public network access. In the proposed solution, one device may be both a HTTPS client and a HTTPS server depending on the purpose of the interactions. For example, the MGMS is a Smart API client for the AMS during Flexibility Forecast and Reserve Verification but a Smart API server for the AMS during Reserve Notification and Activation interactions.

Smart API also supports MQTT over TLS (message queuing telemetry transport over transport layer security) protocol that is based on a subscription model. When the time of the information availability is varying, the MQTT over TLS may be more useful than HTTPS since the client just listens specific topics and receives the information right after it is available instead of continuous polling. In this case, the AMS could execute a role of a broker that spreads the messages between the publishing and subscribing clients (DMS and MGMSs) as the situation requires.

The advantages of Smart API as an interface for remote control and measurement applications include its suitability for integration into large-scale entities, support of transactions, and semantic data definition. The use of Smart API also increases the reliability of secure HTTPS links and MQTT over TLS interactions since Smart API messages can be further encrypted and signed for each message. All these features make Smart API a well suitable for the information exchange interface of the flexibility services described.

IV. Conclusions

The goal of this study was to investigate required communication, information, and functional competencies enabling real-time control of microgrid resources for flexibility services. In order to reach this goal, the ICT analysis consisting of functional analysis and architectural description was implemented on the SGAM.

The ICT analysis has allowed establishing the smart grid architecture for an introduction of flexibility services into management of grid operators. The findings of functional analysis enhance understanding of the motives of potential flexibility market actors to provide and acquire flexibility services. In particular, a spectrum of near real-time services that microgrid resources may deliver for the DSO and TSO management is identified. Furthermore, the analysis presented the overall structure of interactions between the flexibility market actors for the CRP use case and specified the minimum functionality of microgrid management for flexibility services. The architecture description has presented an ICT solution that can realize the functionality of identified flexibility services. The ICT solution relies on semantic web API and delivers common information exchange interface that supports interoperability between flexibility market actors. Further research needs to examine the efficiency and reliability of the proposed ICT solution in real environments.

In addition, this research has brought up many other questions in need of further investigation. One such question is the efficient validation of flexibility services among flexibility market actors where activation of one service would not violate the operation mode of other actors and would not provoke a need for additional flexibility services.

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