Three-layer informatics solution for demand response management in the smart grid context

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Abstract. In consistency with the European Union (EU) vision of creating an electric power system that integrates renewables and enables flexible consumption and generation technologies by means of smart grid (SG) implementation, the main aim of the paper is to develop different level of aggregation mechanisms design that facilitates demand response (DR) and energy systems to utilize up to 100% renewable generation.

In this paper, we will present a three-layer informatics solution for demand response management in the smart grid context. The data model will be developed as a scalable and customized framework using open solutions based on cloud computing.

1. Introduction

Main challenge is to increase flexibility of the grid, complex interactions among large and local or regional energy stakeholders with massive volumes of heterogeneous data (big data challenge). Advancements in SG technologies make possible to apply various strategies for optimization of DR. Its aggregation would essentially accumulate potential consumption schedules and constraints given by small/medium-size consumers for the participation in wholesale electricity markets. However, there are still barriers for widespread adoption of DR aggregation mechanisms at the EU level. According to the Final 10-year ETIP SNET R&I roadmap 2017-26, these include: differences between market structures and legislation; limited awareness and involvement of electricity consumers/prosumers; less motivating incentives for participants; ICT infrastructure at an affordable and reasonable cost compared with benefits; requirements of big data analytics for DR; interactions between aggregators and Distribution System Operators (DSOs); lack of business models for market trading [1].

Implementations of DR aggregator solutions vary over EU countries due to different market structures and development. Advancements in SG technologies enable various options/strategies for the DR optimization in electricity markets. However, there are still barriers for the widespread adoption of DR aggregation mechanisms at the EU level, as emphasized in Final 10-year ETIP SNET R&I Roadmap (2017-26). The community aggregator (CA) concept has been implemented in Nordic countries and can essentially be implemented in other countries (Turkey, Romania), where market development (legislation, rules & policy) is behind compared to Nordic countries. Another concern is about reliability of the ICT infrastructure coupling the consumers, market players and DSOs at an affordable/reasonable cost compared with benefits. In response, our approach demonstrates that DR can be categorized into different levels, from simple CA solution, which can be implemented in any
country in EU, to more complex wholesale electricity market aggregation concept for developed markets. Our approach uses the hands-on experience in the CA concept, while recommending market based DR solutions to expand in other countries. The idea of multi-layer aggregation (MLA) solutions integrates a wider range of requirements to a scalable prototype that leads to better scalability and transferability among the EU countries. Thereby, it has a better chance to disseminate the innovative technologies based findings to a wider audience and markets across EU countries.

Energy Union Package 2015 emphasizes the requirement for moving away from an economy driven by fossil fuels, based on a centralized, supply-side approach, relying on old technologies and outdated business models [2]. This necessitates empowering consumers by providing information, choice and flexibility to manage demand as well as supply. The European Commission is preparing an ambitious legislative proposal to redesign the internal electricity market (IEM) to link wholesale and retail. The electricity market will include many new producers, including renewables (RES), as well as enable full participation of consumers via DR.

The authors of [3] approach the demand response management by proposing an optimal community schedule of hourly electricity consumption considering advanced electricity tariffs such as real-time tariff that flattens the daily consumption curve. The proposed algorithm minimizes the electricity payment by considering the characteristics of electrical appliances and consumption preferences of the residential consumers. It is based on several steps, taking into account adjustable/programmable appliances, local generation sources, storage and common consumption at the community level.

In [4], the authors propose a heuristic-based evolutionary approach based on shifting techniques of several types of appliances at the communities level that treats different consumption sectors such as: householders, commercial and industrial consumption.

Decision-making models for demand response aggregators that act on the wholesale electricity markets are developed in [5]. The aggregators provide different types of contracts that aim to reduce and optimize the electricity consumption. The hourly schedule of the appliances depends on the electricity tariff rate and other provisions of the contracts.

In [6], the authors propose a demand response model bidding framework based on mixed-integer linear programming at the Independent System Operator level that considers consumption preferences and characteristics of the appliances. Demand response management includes measures such as load shifting, curtailments, local generation and storage devices usage.

Comparing with these approaches related to demand response management, the informatics solution proposed in this paper will be developed as an informatics prototype that aims to demonstrate the implementation of DR aggregator solutions across EU countries which have different electricity market structures, regulations and SG implementation stage. The prototype will manage massive data collected from smart meters (SM) and appliances (IoT) for advanced analytics and will be developed on a cloud computing (CC) platform which will enable ubiquitous access to distributed configurable computing resources.

2. Community aggregator multi-layer solution
Due to various stages of development of SG implementation in different countries or regions, our proposal addresses DR aggregating informatics solution in multi-layers beginning from the simplest community aggregator (CA Layer 1) solution. Motivation of the CA will be optimal load scheduling to minimize the community-aggregated electricity payment and consumption peak shaving considering the convenience of individual residents and hourly community load characteristics. Control of demand (i.e., active DR) including electric vehicle (EV) charging stations, distributed renewable energy sources (RES) generation and storage devices (SD) will be addressed in Layer 2. Finally, in Layer 3, aggregation of DR contracts will be considered in the price-based self-scheduling optimization problem to determine optimal DR schedules for participants in day-ahead energy markets as in Figure 1.
Layer 1 can be the initial DR solution given its applicability to any community even without SG implementation. Layer 2 may include several sub-layers depending on SG implementation level. However, Layer 3 requires a DR bidding framework in day-ahead electricity markets, which integrates consumers’ DR preferences and characteristics in the DSO’s market clearing process. ENTSO/E and EDSO outline the main challenges connected with the DR from the grid perspective. ENTSO/E R&D & Innovation Roadmap 2017–2026 highlights the need to activate the demand as a new source/tool for system operation and to integrate it in the planning and operation stages and market design; however it does not accentuates the tasks of activation of the source, leaving to DSOs, aggregators or other players the possibility to do it [7]. In any case, integration of DR has been identified as one of the outstanding issues to be dealt jointly with DSOs. Layer 3 addresses this issue.

The multi-layer aggregation approach covers different structures of markets and regulations as in Figures 2, 3 and 4. It is more applicable since in Europe, the development of SG implementation can significantly vary. For less developed regions, we propose a simple solution 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 and 3) utilizing the block-chain based smart contracts.
Our approach will develop a scalable cloud based platform to provide access to consumers/prosumers and aggregators/DSOs to a complex data framework and models allowing big data and real-time analytics including forecasting, optimization, profiling, and business models. We will also approach the big data and CC challenges related to SG in order to increase consumer awareness and improve the DR mechanisms. We will investigate and verify the high-reliability and low-latency ICT technologies to support real-time monitor and sensing. Block-chain technologies will be investigated to provide smart and flexible contracts. These aspects are among the most prevailing barriers for the widespread adoption of DR aggregation mechanisms at the EU level, as underlined by Final 10-year ETIP SNET R&I Roadmap and EC Energy Union Package 2015.

3. Data framework

The data framework contains several tiers that can be customized based on each layer. These tiers will allow complete customization, using different technologies for interconnecting sensors through smart meters (SM-Tier); fast processing and real-time analyses through big data (BG-Tier); high-reliable, low-latency, secure and performant data transmission and management with relational databases (RB-Tier); historical and advanced analytics through data warehouse (DW-Tier) as in Figure 5.
The data framework will be developed on multi-tier architecture for high scalability, using open standards for wider integration and adoption. For SM-Tier, we’ll consider OpenIoT, FIWARE & IoT-A ARM platforms currently adopted and standardized in EU. To achieve real-time information sensing and collection, we’ll develop and demonstrate ultra-reliability low-latency communications based on short-packet. For BG Tier, we’ll consider optimization methods, such as: hash partitioning, parallel execution, dimensionality reduction, Map Reduce. For load profiles (LP), we will use artificial neural networks (ANN) algorithms (Self Organizing Maps, k-means, Fuzzy C-Means) for clustering data across multiple nodes, with different type of SM, preserving consumers’ location, weather, day type and dynamically adding particular characteristics. For forecasting, ANN algorithms will be developed/run on both historical and online data for short term load forecast (LF).

Optimization algorithms will be developed for each layer. Layer 1 provides optimal load scheduling of the community to minimize the electricity payment considering the convenience of individual residents and hourly community load characteristics. Inputs include: LP, LF, cost of electricity consumption, and preferences of the consumers in the community as constraints included on the hourly utility load (defined as CA load minus the local generation). Lagrangian relaxation (LR) will be applied to decouple the utility constraint and provide tractable sub-problems formulated as mixed-integer programming (MIP).

Optimization in Layer 2 includes various contract offers for the customers for load curtailment and shifting, local generation, managing electrical vehicles (EV) charging stations and storage systems as possible strategies for hourly load reductions. The aggregation of DR contracts is considered in the proposed price-based self-scheduling optimization model to determine optimal DR schedules for participants in day-ahead energy markets. We’ll use block-chain to develop smart and flexible contracts.

Figure 5. Tiers for each layer
In Layer 3, a hierarchical DR bidding framework in the day-ahead energy markets, which integrates consumers’ preferences and characteristics in the DSO’s market clearing process, will be developed. Aggregators can submit offers to the DSO which will optimize final decisions on aggregators’ DR contributions to wholesale market. The DSO applies MIP to the solution of the proposed DR model in the day-ahead market clearing problem.

As an innovative concept, the prototype will be developed as a scalable-customized cloud computing web-services using open standards, models and connectivity as in Figure 6.

![Figure 6. Tiers for each layer](image)

The prototype will be developed modular and will be configured based on the requirements of stakeholders. Each proposed layer of the solution will have its innovative and original elements. The prototype’s models will be developed on a data framework with multiple tiers (SM, BG, RB, DW Tiers) providing reliable and consistent data for the models and algorithms including LP, LF and electricity price from the utility, feed-in tariffs for RES, etc.

For integrating SM data, we’ll develop agents to connect sensors with different communication protocols (ZigBee, LORA, WiFi, Wi-SUN) in order to load custom data in the BG-Tier. One of our key innovations is to support ultra-reliable low-latency communications based on short-packet for supporting real-time SM data transmission and corresponding actuation, which is very important to multi-layer systems. The platform can be extended to connect sensors from other utilities (gas, heating) and enabling Advanced Metering Infrastructure (AMI).

The SM and BG Tiers will be used for real time analyses and for developing the algorithms for controlling, monitoring & online forecasting and optimization. The SM-Tier will be implemented on an edge computing architecture to perform data processing at the edge of the network, thus reducing the communications bandwidth between SM and BG-Tier. Relational databases and big data are complementary technologies that process data at an impressive rate of more than 10TB (terabytes) per hour. Through our integration framework, we’ll first process big data in the BG-Tier on a distributed, scalable file system, such as HDFS (Hadoop File System) and develop query patterns with processing engines (Hive, Drill, Impala or Presto). For data processing, we’ll develop algorithms that are executed in parallel and extract relevant data based on a pattern matching criteria. These patterns will be defined based on the requirements provided by the aggregator/DSO concerning their analytical perspective. At the BG-Tier, we’ll develop forecasting algorithms based on ANN (feed-forward, deep-learning). They will be developed online, receiving immediate feedback and improving subsequent predictions in contrast to statistical methods. Data dimensionality will be adjusted for different time horizons, for example for very and ultra-short term forecasting the algorithms will perform on detailed data (minutes), since for STLF data will be aggregated hourly over locations or consumers’ profiles. For LP we’ll use distributed data mining with multi-node processing based on
Self Organizing Maps, k-means and fuzzy c-Means. Thus, data regarding type of consumption, tariffs schemas’ influence, injection of RES, EV usage is transformed into a valuable information for aggregators/DSO. Optimization algorithms will be developed based on LR and MIP techniques to formulate the complex dynamic optimization problems that include several constraints at each layer. In Layer 1 LR will be applied to decouple the utility constraint and provide tractable sub-problems formulated as MIP model. A hierarchical DR bidding framework in the day-ahead markets, which integrates customer DR preferences & characteristics in the DSO’s market clearing process, will be developed in Layer 3. The DSO applies MIP to solution of the proposed DR model in the day-ahead market clearing problem.

From BG-Tier, some aggregated data is loaded into RB-Tier to allow integration with on premises Energy Management Systems (EMS) already installed at aggregator/DSO. For example, the LP data will be partitioned by locations and consumers’ profiles and stored in RB-Tier for integration with EMS. The DW-Tier will be developed on top of BG and RB tiers and will be subject oriented towards the business analyses regarding consumers’ behaviour and wholesale electricity markets. Analytic solutions require data governance, data quality and stewardship that are absolutely critical and are achieved only through the DW-Tier. At this layer we’ll developed a set of algorithms for analytical purpose and key performance indicators (KPIs) reporting. The framework will offer scalable web-services for targeted users. The aggregators/DSO will analyse data through an online portal available as web-services in CC platform. For consumers, the web content will be customized based on their preferences & requirements (monitoring/controlling/scheduling the appliances, real time billing information, micro-generation and SD). A section of the portal will be developed as a simulator similar to a computer game to motivate consumers to optimize their electricity consumption and to increase their awareness towards energy efficiency.

4. Conclusion

The full liberalization of the markets will lead to competitive prices and services offered by electricity suppliers including aggregators. Through business models, the prototype will allow suppliers to configure their tariffs and to attract new consumers groups as well. This will bring a significant benefit to prosumers, who will obtain several incentive options. They will play an active role in DR, having the possibility to gain profit, apart from saving money.

There are several impacts the consortium find relevant and beneficial for society. The multi-layer aggregator services encourage active participation of prosumers through differentiated tariffs between locally and centrally produced power, and through a market, handle storage and DR. This enables local markets to solve many of the issues regarding implementation of SG, especially around incentives, business models and adoption. This active participation will allow consumers to reduce their electricity bill maintaining their comfort. The solution opens up for new innovative business models where companies can develop new products combining wholesale and local markets, and energy services such as flexibility management. Again, this increases the economic benefits for participants willing to take active roles in local energy markets.

In addition, by aggregating and increasing the share of local RES, the costs for upgrading regional and national grid is lowered. By balancing the consumption and production in a local area, especially during peak hours, less energy is imported from the centralized grid and thereby reducing the amount of energy transported through the transmission grid. As a consequence, grid costs for end-users will diminish.

The proposed solution will also contribute in reducing the prices by making a market for the local energy produced, and thus increasing the incentives for buying local energy. In a functioning market, the price difference between locally produced energy and wholesale energy due to transportation costs, also creates incentive for consumers to become prosumers and sell energy to the local market.

Multi-layer aggregator concept needs new market polices, legislation and/or incentives schemes for SG infrastructure. By demonstrating that the solution can, under the right circumstances, give the desired effects, the pilot trials will demonstrate how such regulative bodies can be structured for the desired impact for adoption of SG technologies.
5. References

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