Journal of Energy Storage 17 (2018) 203–212

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

A simulation framework for assessing the market and grid driven value of flexibility options in distribution grids

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ARTICLE INFO

Article history:
Received 30 September 2017
Received in revised form 25 December 2017
Accepted 10 March 2018
Available online xxx

Keywords:
Flexibility options
Smart homes
Virtual power plants
Operational planning
Grid congestion management

ABSTRACT

The increasing share of renewable distributed energy resources (DERs) entails a rising number of congestions in the German distribution grids, such as voltage band violations and overloading of network assets. Consequently the need for grid expansion increases [1]. A politically promoted alternative to grid expansion is managing congestions by the preventive use of flexibility options, such as flexible generation, load management and storage systems [2]. However, preventive congestion management is not yet established in distribution grids. Thus, various measures are under discussion to stimulate the provision of flexibility options by its owners for concerns of congestion management. Assessing the suitability of solutions among these congestion management measures (CMMs) requires a realistic modeling of grid operation, energy system structures and the behavior of the owners of DER and flexibility options.

The intended application of the presented simulation framework is consequently the assessment of the macro- and micro-economic effects of preventative CMMs in distribution grids. Supporting that goal, the design of an agent-based simulation framework, which incorporates detailed optimization models for simulating the behavior of grid users (owners of DER and flexibility options) and Distribution System Operators (DSO) is presented. Exemplarily it is applied on a realistic distribution grid use case. The simulation framework enables analyzing the consequences of the grid users' interaction with the DSO following defined CMMs. Within the framework, the grid users are modeled as individually or market driven oriented users, who both aim at improving their micro-economic situation. The DSO's operational target is the minimization of congestion management costs under application of several CMMs.

The exemplary application focuses on four congestion management concepts, such as flexible tariffs and a market-based flexibility provision. The chosen use case comprises a congested distribution grid with high PV penetration and grid users at the medium and low voltage level. In the use case, the alternatively necessary curtailment of renewable energy can be reduced from 15% to 35% depending on the considered CMM. The most promising CMM (a market-based flexibility provision) reduces the DSO's congestion management costs by 33%, without degrading the grid users' economic situation. Future work will advance the analyses based on a comprehensive database of realistic distribution grid scenarios.

1. Introduction

The decentralization process of the German generation structure implies an increasing feed-in by DER in distribution grids, causing new challenges for the planning and operation of grids. In the context of grid operation, the need for congestion management measures, such as the Redispatch of power plant schedules or curtailment of renewable feed-in (feed-in management), is strongly increasing as a result of the high feed-in by DER [1]. The resulting costs of congestion management are socialized via adjustment of grid usage fees. Facing the strongly increasing congestion management costs, the question arises how the macro-economic costs can be minimized by a preventative use of flexibility options, such as energy storages or flexible generators and loads. While preventive congestion management instruments are established in transmission grids (Redispatch), the DSOs' scope of action is limited to feed-in management. Thus, flexibility options provide an appropriate option to complement and prevent feed-in management [2].

However, these flexible technologies generate economic value for their owners. Hence, the integration of flexibility in grid operation leads to a conflict of interest between the involved

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https://doi.org/10.1016/j.est.2018.03.003
2352-152X/

actors. Relevant actors beside the DSO are the owners of renewable DER or buildings, equipped with flexible technologies. On the building level, the owners may act as prosumers, who optimize the individual energy procurement by using synergies of their technology portfolio (e.g. solar power systems, combined heat and power (CHP) plants, storage systems, flexible loads). Alternatively, the use of these flexible technologies is attractive to DSOs and aggregators (Virtual Power Plants, VPPs). VPPs aggregate the capacities of technologies to maximize the profit of their clients (owners of renewable DER and flexibility) at the spot and control reserve markets and may act as a service provider to the DSO in procuring flexibility for grid operation.

Towards the coordination between the grid and market driven operation of DER and flexibilities, the German Federal Network Agency published the idea of a traffic light concept. It defines three network phases (green, amber, red), which are classified based on network state forecasts on behalf of the DSO [3]. The green phase represents an expected uncongested network and enables free market transactions, whereas the red phase applies, if interventions such as feed-in management are the ultimate option. To prevent the red phase, predicted congestions are desired to be solved by procuring flexibility in the amber phase. However, the measures to stimulate the flexibility provision for congestion management remain undefined. Thus, several CMMs are discussed as design option, such as network state dependent load tariffs and local flexibility markets (e.g. [4–6]). All eligible CMMs have to satisfy a non-discriminatory (cost based) technology prioritization [3]. Thus, precisely curtailing the feed-in of renewable DER may perform more cost-efficiently as other flexibility options. Due to that claim for technology neutrality, the term DER subsequently summarizes all kind of generators, loads and storages.

On the whole, assessing the impact and feasibility of new CMMs, requires detailed models to consider the behavior and opportunity costs of DSOs, VPPs and prosumers with regard to flexibility deployment. Hence, relevant scientific works in the field of coordinated market and grid driven operation of DER will be discussed subsequently, to work out the relevant elements of the proposed modeling approach.

1.1. Scientific works on market- and grid-driven operation of DER

With regard to **market applications** and the **provision of ancillary services**, numerous research activities address a coordinated operation of flexible technologies. While several publicized models focus on the market participation of particular technologies such as storages ([7,8]), others pursue approaches, which coordinate a pool of DER to maximize common market revenue. Generally, the coordinating approaches can be inspired by *centralized* and *decentralized* coordination schemes. The choice of a coordination scheme depends on the practitioners preferences towards optimality of solutions and scalability of simulation. Examples for *decentral* approaches with focus on market applications are [9,10]. Both focus on self-organizing planning procedures, to reduce the complexity, which inherent to large problems in *central* approaches, guaranteeing optimality (such as [11,12]). However, *central* approaches can increase the robustness of market schedules for DER in VPPs by using the methods of stochastic scheduling to face different feed-in scenarios of renewable energies ([13–15]).

The aforementioned market-driven approaches neglect possible network overloads resulting from the DERs market schedules. Thus, another research domain in the field of coordinated DER operation focuses on active support by DER towards **grid operation** and **congestion management**. Approaches in this field both consider individually applicable (such as [16]) and coordinated control schemes for DER in grid operation algorithms. Several coordinated DER control approaches neglect the use of a grid operation in combination with controllable network assets (e.g. [17–19]), which is incorporated consequently in recent publications. The design of the models, which satisfy this combination, can again be classified in *decentral* ([20–22]) and *central* approaches ([23]).

The various so far named approaches focused on partial aspects, but not on **coordinated market and grid driven** DER operation, which is considered in recent publications ([24–27]). These approaches ensure an economically optimal DER deployment with regard to market and grid application. At the same time, they neglect modeling concrete mechanisms to incentivize the deployment of local flexibility and possible design options for the amber phase. Consequently, several authors pursue the investigation of the potential for local flexibility markets ([28,29]). However, they focus on determining the theoretical optimum for the flexibilities' potential, since they assume the omniscience of one central actor regarding all relevant processes in the distribution grid.

1.2. Elaboration of relevant elements for the proposed simulation framework

In order to achieve a realistic assessment of the impact and feasibility of design options for the amber phase, detailed models for flexibility deployment in grid and market applications are crucial. Basically, the presented approaches provide detailed solutions, but overvalue the flexibilities potential due to neglecting the fact of an unbundled power system and different locally available information (to actors). As a result, there is an evident need for approaches, which consider separated roles and actor-specific available information. This can be met by using a modular simulation framework, whose modules (agents) reproduce the behavior of the involved actors depending on chosen coordination schemes. Simultaneously, modular approaches reduce the complexity of system optimization, facing the demand to consider realistically sized distribution grids with a multitude of network buses and installed technologies.

Generally, many modular simulation frameworks have been developed within the context of Smart Grids and the deployment of flexible technologies. However, many of these environments were originally developed with a focus on islanded micro-grid operation and primarily address aspects of system dynamics based on corresponding software engines ([30–34]). In contrast to that, the consideration of steady system states and lower time domains (minutes) is sufficient to address the research question of a techno-economical assessment. In this context, rather a robust interfacing with powerful optimization solvers (such as CPLEX [35]) and established grid optimization tools (such as Matpower [36]) are highly relevant. Further publicized frameworks focus on a co-simulation of power and information flow in distribution grids ([37–41]). Basically, an adequate ICT infrastructure is mandatory to enable interactions between actors in terms of congestion management, but its costs must be recovered by additional revenues or savings in grid operation. Hence, prior to communication handling, the question for the potential value, generated by a rollout of ICT (for a given and technically working infrastructure) is to be assessed.

Consequently, a modular simulation framework to assess the techno-economic potential of an organized market and grid driven flexibility operation is presented. To perpetuate a high quality of efficiency in flexibility deployment, the single modules will use central optimization approaches.

2. Proposed simulation framework

Agent-based modeling offers a modular realization for simulation models and thus a clear separation of different actors (agents)