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Optimization problem for meeting distribution system operator requests in local flexibility markets with distributed energy resources

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HIGHLIGHTS

- We propose a new optimization problem for scheduling flexible resources to meet distribution system operator requests.
- We included loads, generators and batteries as flexibility resources.
- The optimization problem minimizes the SESP operation cost.
- We perform a case study to validate the work presented.
- We perform a test in the laboratory platform.

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ABSTRACT

The increasing penetration of distributed energy resources in the distribution grid is producing an ever-heightening interest in the use of the flexibility on offer by said distributed resources as an enhancement for the distribution grid operator. This paper proposes an optimization problem which enables satisfaction of distribution system operator requests on flexibility. This is a decision-making problem for a new aggregator type called Smart Energy Service Provider (SESP) to schedule flexible energy resources. This aggregator operates a local electricity market with high penetration of distributed energy resources. The optimization operation problem of SESP is formulated as an MILP problem and its performance has been tested by means of the simulation of test cases in a local market. The novel problem has also been validated in a microgrid laboratory with emulated loads and generation units. The performed tests produced positive results and proved the effectiveness of the proposed solution.

1. Introduction

Smart grids play a key role in the transformation of power systems. One of the main goals of the implementation of a smart grid is to integrate Distributed Energy Resources (DER) into the distribution grid to complement generation from bulk sources. Several benefits have been linked to the deployment of smart grids: reliability increase, carbon footprint reduction, increase in revenue and a decrease in consumer energy expenses [1]. However, the road to their successful implementation presents challenges at different levels: design, operation, control, energy storage technologies integration and regulatory issues [1].

Focusing on operational challenges, the evolution driven by smart grids is shaping a scenario with new energy exchanges. In this context, new actor and roles are materialising within the power system leading to new operational procedures.

A representative example is the appearance of the prosumer concept, which combines the consumer, storage and local level generator capabilities. These capabilities enable electricity and economic transactions in the so-called local electricity markets [2], also known as micro-markets in some studies [3,4]. In the near future, an energy exchange scenario can be envisioned with several geographically allocated local markets. Such markets managing flexible resources can address high penetration of DER at distribution grids [3].

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Recently published literature provides a wide variety of definitions of the flexibility in power systems [5,6]. In this paper, the following definition is adopted: Flexibility expresses the extent to which a power system can modify its electricity production and consumption in response to variability, expected or otherwise [7]. Additionally, upward regulation is defined as increasing generation or decreasing demand, and downward regulation means decreasing generation or increasing demand. Alizadeh et al. [8] classified flexibility effects on power systems chronologically as short-term, mid-term and long-term categories.

According to the Smart Energy Collective alliance definition [9], the role of Aggregator (AGR) consists of accumulating flexibility in active demand and supply. The AGR seeks the lowest costs to meet the energy demand of his portfolio taking the costs for capacity usage into account. Additionally, van den Berge et al. [10] and the Universal Smart Energy Framework (USEF) report [11] defined four flexibility customers: Distribution System Operators (DSO), Balance Responsible Parties (BRP), Transmission System Operators (TSO), and Prosumers. DSO and TSO are interested to purchase flexibility to manage grid congestions and reduce upgrading grid costs. BRP and retailers can use flexible resources to manage their portfolio and reduce deviation penalties and operation costs. Finally, prosumers can use their flexibility capabilities to reduce the electricity bill.

The paper is focused on flexibility in distribution grids with high penetration of renewable power generation and other distributed resources such as storage systems. The increasing amount of DER connected to distribution grids can compromise power quality in terms of voltage limit violations, line overloads or instabilities. Additionally, their variability can pose issues in grid operation due to voltage fluctuations, limiting the grid hosting capacity to integrate distributed generators [12,13]. Redundant transformers can avoid operating the grid close to its voltage limits, but the required expenses are considerable leading to the necessity of finding alternative solutions like storage [14] and demand response [15]. Furthermore, if some loads, distributed generators and batteries connected to distribution networks could operate according to grid necessities, DSO would manage networks avoiding these power quality issues. Hence, a local flexibility market (LFM) for distribution grid operation could provide the required trading environment avoiding additional investments. Moreover, in further developments not included in the present work, LFM will compensate local deviations due to forecasting errors reducing penalties in the wholesale markets and they will also participate in balancing markets managed by TSO.

The contents of this study are structured as follows. Section 2 includes the literature review about distribution grids with high penetration of DER. Section 3 describes the system under analysis and its architecture to identify the main actors and their interactions with the SESP. The optimization problem defined in this study, detailed in Section 4, is executed by the SESP to determine the system operation scheduling. The case study exposed in Section 5 shows the simulation results which are validated in a scaled experimental platform in Section 6. Finally, conclusions are drawn in Section 7.

2. Literature review

Following the recent contributions on the distribution network operation with high penetration DER, this section compares different solutions proposed in the literature. In order to compare different methodologies, Kok et al. [16] classified distribution-level energy management approaches in four categories: Top-down switching, centralized optimization, price-reactive and transactive energy systems. The present analysis is focused in two categories: local markets with a centralized approach and transactive energy systems. Classical demand response programs using a top-down switching methodologies and price reaction approaches are not included in the comparison because they use one-way communication system considering end-user as a passive actor.

2.1. Centralized local flexibility market approaches

Previous proposals presented approaches like Virtual Power Plants (VPP) that aims to emulate the behaviour of conventional generators aggregating DER [17,18]. First of all, Braun et al. [17] reviewed the aggregation approaches of DER comparing VPP with incentive-based indirect control systems. Pudjianto et al. [18] distinguished between commercial and technical VPP. Commercial VPP facilitates DER trading on wholesale markets and technical VPP provides services to support transmission system operation. Different authors proposed scheduling algorithms for VPP [19–23] Nevertheless, VPP are not end-user focused and they do not provide the framework for participants willing to be active traders with certain negotiation power. Alternative proposals like local markets and transactive energy systems are following the EU recommendation to put consumers at the heart of the energy markets by ensuring that they are empowered and better protected [24].

Comparing similar local market-based proposals to the present work, Kamyab et al. [25] exposed an optimization problem formulation to reduce the energy cost in energy community scheduling distributed energy resources (DER). Nguyen et al. [26] presented an optimization problem for BRP day-ahead portfolio management to compensate load and supply forecasting deviations. Finally, Torbaghan et al. [27] operated the local flexibility market to bid in wholesale markets. These three proposals are addressed at providing flexibility services to the BRP for portfolio management without receiving DSO requests.

Finally, Meese et al. [28] presented a case study for using flexibility to reduce the electricity bill from the prosumer perspective.

Previous works about constrained distributed grid operation like Eid et al. [29] and Verzijlbergh et al. [30] compared different frameworks for managing flexible resources to reduce network peaks but the corresponding operation formulation is not included. Esterl et al. [31] analysed the impact of flexibility on distribution grids without specifying the operation optimization problem. Esmat et al. [32,33] presented a similar problem using demand response but they assumed that activation decisions of each device are made by the DSO. Based on the queries to different European DSO in EMPOWER project, DSO are currently not interested in taking such decisions and they are more inclined towards simpler approaches without many interactions [34].

In contrast and from the DSO point of view, Spiliotis et al. [35] proposed a fix rate local flexibility market for managing flexible demands as a long-term planning tool for DSO. This aims to solve the expansion problem allocating flexibility needs and including grid expansion costs to alleviate grid constraints.

Moreover, Huang et al. [36] presented an optimal power flow algorithm to manage grid congestions using flexible resources. A similar approach is presented by Nguyen et al. [37] who considered that the DSO publishes the transformer capacity. Moreover, their proposal included a multiple AGR per transformer case assuming their availability to share information. However, not all consumers connected to the same distribution transformer have to be members of the same BRP and different BRP could not be interested to share information. Nevertheless, none of the two algorithms are applicable in the current European regulatory framework due to the current unbundling principle: there is a legal separation between network management and commercial activities [38]. Therefore, AGR and BRP are not allowed to know the grid parameters either grid status. That makes the inclusion of grid congestion constraints in the optimization problem not feasible in Europe. Moreover, DSO are not allowed to schedule flexible resources affecting the BRP portfolio balance.

In contrast in this work, AGR receives DSO requests without knowing grid status information to solve grid congestion problems in the daily basis. In order to attend its demands, AGR controls flexible assets using a market-based methodology.