Sustainable Energy, Grids and Networks 14 (2018) 35–46

Contents lists available at ScienceDirect

Sustainable Energy, Grids and Networks

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

Distributed flexibility management targeting energy cost and total power limitations in electricity distribution grids

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ARTICLE INFO

Article history:
Received 31 March 2017
Received in revised form 16 February 2018
Accepted 3 March 2018
Available online 13 March 2018

Keywords:
Demand Management algorithms
Distribution grid management
Communication protocols
Distributed system
Testbed evaluation

ABSTRACT

Demand Management uses the interaction and information exchange between multiple control functions in order to achieve goals that can vary in different application contexts. Since there are several stakeholders involved, these may have diverse objectives and even use different architectures to actively manage power demand. This paper utilizes an existing distributed demand management architecture in order to provide the following contributions: (1) It develops and evaluates a set of algorithms that combine the optimization of energy costs in scenarios of variable day-ahead prices with the goal to improve distribution grid operation reliability, here implemented by a total Power limit. (2) It evaluates the proposed scheme as a distributed system where flexibility information is exchanged with the existing industry standard OpenADR. A Hardware-in-the-Loop testbed realization demonstrates the convergence and effectiveness of the approach and quantitatively shows a power quality improvement in the distribution grid.

1. Introduction

Distributed generation and new loads in the low voltage (LV) grid, such as electric vehicles, strongly change the consumption patterns of LV grids and may cause needs for reinforcement of grid infrastructure. Alternatively, the investment could be deferred provided that the flexibility in the LV grid can be exploited. However, many Demand Management approaches [1,2] are driven by economic interests and market aspects; but market considerations cannot be applied to small geographical areas, which would be required to address local grid overload. Some countries therefore allow a second level of flexibility control [3], which however can only be applied in certain grid-critical situations.

Demand Management, also called Demand Side Management or Demand Response, has emerged already in the 1970s, but experienced a renaissance with the development of distributed generation, distributed energy resources, and flexibility reporting and usage [4–7]. When market clearance prices are considered in simple Demand Management schemes, in which the local controllers are only price takers, but do not participate on the marketplace, load peaks may be artificially created when prices are low [5]. Therefore, either more complex, real time price response schemes are needed, or the created peaks may need to be shaved subsequently.

This paper takes a different approach by combining the two targets, energy cost minimization and peak shaving, explicitly in the objective function of the Demand Management optimization algorithms. As the behavior of the overall Demand Management system is determined by several entities in a control hierarchy and is influenced by the interaction protocols deployed between them, the **analysis of the overall integrated system behavior** is complex and needs to be carefully designed and executed. In the evaluation of the proposed algorithms, this paper put its emphasis on the fact that the resulting Demand Management system is a distributed system, in which information and setpoints are exchanged between remote entities via communication networks and protocols. Furthermore, part of the data is transported and aggregated via DSO systems, so different information paths need to be considered. The paper considers a realization of the Demand Management algorithms on top of an open industry standard OpenADR [8]. The two important parts of the objective function of the proposed Demand Management algorithms, the resulting effective customer energy prices and the impact on the distribution grid, are evaluated as part of the paper in a hybrid simulation setup and

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https://doi.org/10.1016/j.segan.2018.03.001
2352-4677/

in a distributed implementation using a real-time Hardware-in-the-Loop co-simulation approach for the distribution grid and the communication networks.

The rest of the paper is structured as follows: Section 2 positions the paper with respect to the state of the art. Section 3 summarizes the existing architecture that is adopted for the proposed Demand Management system. Section 4 presents the new demand optimization algorithms implemented in controllers at the customer and at the central site, which jointly address energy costs and power limitations. Section 5 describes the implementation of such Demand Management solution using available industry standards for communication between the controllers. Section 6 reports and discusses evaluation results based on a non real-time simulation for different Demand Management scenarios in order to verify the convergence of the proposed algorithms. Section 7 presents an implementation of the Demand Management algorithms and the related communication protocols on a real-time Hardware-in-the-Loop system and shows the resulting benefits for the distribution grid operation. Section 8 concludes and presents further research directions.

2. Relation to state of the art

2.1. Demand management architectures and approaches

Demand Management (DM) schemes are able to shift the consumption in time and are normally classified in incentive-based (direct load control), price-based indirect control or a combination of both [5]. A number of distributed system architectures have been developed to support the DM functionality. The Mas2tering project [9] has developed a system architecture for reporting and tracking energy flexibility at the LV grid level. At the core of the Mas2tering platform is a network of multiple intelligent agents (MAS) that can be associated to a DSO, prosumer or aggregator component, leading to flexible but complex interactions. The project flexiciency [10] developed a system architecture for information exchange between DSO, service providers such as retailer, aggregator and a market place in order to facilitate energy efficiency using metering data, flexibility participation, demand response and local energy control. There is a vast literature on control of energy flows in LV grids, depending on the control time scale. According to the classification in the survey [11], we selected a distributed architecture for a secondary control (energy management) approach, meaning that the customer side provides the first local control level on its DERs, whereas the aggregator provides the top control level.

The architecture adopted in this paper is from [12] and is summarized in Section 3. Similarly to the MAS approach, the adopted architecture uses agents placed at different nodes; in the case of this paper these are specialized agents defined in the standard **OpenADR 2.0b.**

Price-based DM schemes are characterized by dynamicity of price releases: for example, day ahead prices are issued for the whole next day, whereas real-time prices have a much shorter price announcement horizon, e.g. every hour. Real-time pricing systems are complex because a full feedback loop has to be built between the demand and the generation market, so that prices react on the demand changes and vice versa [4,5]. Modeling the market and price building goes beyond the scope of the paper, therefore we assume that the households are price takers and use day-ahead prices.

As the DM functionality is heavily dependent on the underlying communication network, privacy and security threats related to the deployment of the OADR 2.0 technology are relevant, see [8]. Thus, in order to secure the exchange of messages between Virtual Terminal Node (VTN) and Virtual End Node (VEN), OpenADR uses X509v3 certificates and the TLS1.2 protocol with SHA256 ECC or RSA cipher suites, see Chapter 10 in [13].

2.2. Optimization algorithms for demand management

If demand and energy price forecasts are available, the energy management problem can be formulated as resource scheduling problem, using mixed integer optimization techniques. At the customer the consumption has to follow the imposed power setpoints as discussed in [14,15].

Flexibility concepts have been used in the context of electric vehicle charging and flexible home consumption [12,16]. In [15], the authors use the energy stored in the EV fleet and the bounds of this energy to optimize the charging schedules at the fleet level. In [17], the authors present FlexLast, a solution for controlling the power consumption for cooling in supermarkets, based on the flexibility reporting. Energy prices together with flexibility information have been used in a scheduling model in [18].

In this paper, the objective in the design of the DM scheme is on one side to minimize the energy costs (price-based DM), and on the other side to limit the aggregated load (as typically done by direct load control). As shown in Section 4.3, the latter goal will here be achieved at the aggregator by using the power flexibility information from each CEMS together with the total load of the remaining distribution grid customers for the setpoint computation.

2.3. Demand management as distributed system

Since Demand Management works with a large number of geographically highly distributed grid assets, and many of the latter are placed at buildings or industrial plants that are already having an active communication access, the use of Internet connectivity or other already deployed communication infrastructures is necessary to keep the cost of deployment low. On the other hand, such communication networks may show variable delays and also communication outages, either short term leading to packet loss, or even longer communication outages causing dropped connections and lack of real-time information for several minutes to hours [19–22]. Therefore, DM solutions should be made robust such that they can operate under variable communication scenarios.

Due to the complexity and multidisciplinary nature of running demand management over imperfect communications network without endangering customers or businesses, not much assessment of non-ideal communication impact exists. However, many papers point out the criticality of such assessment, e.g. [23], where scheduling of consumption is assessed, while the network performance is only addressed qualitatively. Ref. [24] mentions a larger Danish project, EcoGRID [25], which ran demand management tests on the island Bornholm for long duration, however, relied on a stable communication infrastructure commonly found in Denmark. For EcoGRID, OpenADR and IEC 61850 where used. Reference [26] reviews different aspects of Demand Management and ICT, however, stays with a qualitative comparison. Reference [27] discusses the use of communication in electrical charging situations, positions functionality among actors and discusses also options for communications and their pros and cons, but does not do any quantitative assessment of how communication impacts demand management operation.

This paper presents a demand management approach, which utilizes planning over time horizons of several hours and subsequent adjustments of earlier made plans using a rolling time window of updates which are then sent to controllers. That way the approach **achieves to be robust to communication disruptions** of durations up to a few hours in certain reference test scenarios.

2.4. Existing evaluation approaches and their application to demand management

Most of the existing work on Demand Management uses either simulations for evaluation [28,29] or uses numerical