Demand Response for Increased Grid Flexibility: The case of Finland

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Abstract — The growing penetration of intermittent renewable energies and of other distributed energy resources in the power system, together with the technological pressure imposed by the emerging smart grid infrastructure has resulted in problems related to the intermittency and bidirectionality of the grid. This context has originated an urgent need for improving the energy system’s flexibility, so that appropriate levels of balancing and reserve power, as well as greater reliability, can be achieved. The optimized use of demand-side energy resources, in particular the implementation of large-scale demand response (DR), could become instrumental in achieving this goal. However, efficient harvesting of potential benefits of DR requires sophisticated methodological approaches. This study introduces a new hybrid approach for maximization of DR benefits, which combines market and network-based DR schemes, thus facilitating the efficient use of the electricity distribution network infrastructure and enhancing operation of the power system and electricity markets as a whole. A case study that demonstrates and validates the proposed DR optimization approach is also presented. The results show that the consideration of both network and market-based DR optimization objectives in parallel can provide substantial economic benefits for the involved market parties.

Index Terms—DR, Economic benefits, DSO, Load control

I. INTRODUCTION

The growing integration of intermittent renewable energy sources (RES) in electric grids is today a key issue in the power sector that poses challenges to the management of the vital balance between electricity demand and supply [1]. To aggravate this scenario, the benefits of using traditional power balancing sources, such as adjustable fossil-fueled condensing power plants, are beginning to fade, as these continue being replaced by more technologically advanced sources [2]. On the demand side, the impact from energy efficiency measures and the ongoing reshaping of the characteristics of electricity demand, often including peak loads rising, for instance through the rising penetration of distributed energy resources (DER) such as electric vehicles and heat pumps, are also disrupting the power system [3]. For transmission system operators (TSOs), maintaining reserve power plants available for meeting occasional power peaks, which will happen in these emerging circumstances, is vastly expensive. In addition, the increase of peak loads in both MV and LV grids, implies significant risks for the DSO, as it may result in additional network investments. [4]. Furthermore, revenues not only for DSOs but also for energy retailers will decrease, if the amount of energy supplied to customers reduces, as result of improving energy efficiency and of increasing DER penetration.

This context described above reflects a pressing need for improving the evolving energy system’s flexibility, so that appropriate levels of balancing and reserve power, as well as greater service reliability, can be achieved [5]. The optimized use of demand-side energy resources, in particular the implementation of large-scale demand response (DR), could become instrumental in achieving this goal [6]. DR also improves electricity market performance, for instance by cutting electricity price spikes [7]. Moreover, increased demand side flexibility allows higher RES penetration in the power system, mitigates market power of market players, and prevents prices from going significantly over production costs [8]. From the viewpoint of the DSO, DR is a valuable resource for distribution network management. It can enable the DSO to curtail peak power in the distribution networks and thus to defer or avoid expensive network investments. Many other benefits from DR, some highlighting its particular value to the distribution business, have been described in the literature, for instance in [9]. Equally, various DR approaches have been documented. For instance, DR may be used to avoid or postpone grid enhancement investments [10], to manage risks and/or maximize profits of the electricity retailer in electricity markets [11], and to balance variations of the intermittent renewable production [12]. Noticeably, very few DR applications, if any, propose combinations of different approaches. Such hybrid applications may bear potential for a more efficient use of demand-side energy resources and for greater maximization of DR benefits.

Despite the above, so far, the impact of DR implementations has been marginal, as large-scale programs have not been yet become widespread. The lack of understanding of DR economics may be a key factor in this. If DR benefits become better understood, then a more favorable environment for large-scale incentivization may emerge.
Related barriers to large-scale DR implementation include passiveness among customers, slow penetration of DR technology, uncertainty about recovery of the investments, and unclear responsibilities of market parties [13]. On the other hand, some worth mention developments towards large-scale adoption of DR have been taking place. In Finland, the universal penetration of smart meters, which are key in smart grid operations, has provided a basic platform to facilitate that goal [14]. In addition, a vast amount of DR resources, such as residential and commercial HVAC (heating, ventilation, and air conditioning) loads that could be harvested, has been identified. Presently, in the country, around 1800 MW of existing residential heating loads can be controlled using installed smart metering infrastructure [15].

This paper introduces a comprehensive demand response approach that aims at maximizing DR benefits by combining network and market-based DR. As explained, this approach complements a gap in the literature. In addition, a Finland case study demonstrating the proposed approach is introduced.

II. REVIEW OF KEY ASPECTS IN DEMAND RESPONSE

Three specific aspects can be considered as key to the implementation of a comprehensive DR approach.

The first aspect is “Customer Response”, which relies on the type of DR program at aim. Such programs are most typically divided as being either incentive or price-based. In price-based DR programs, the customer response is captured as a reaction to the different value and cost of electricity in different time periods (for example via time-of-use - TOU, real-time, or other dynamic pricing models). One of the main advantages of price-based DR is that it can enable customer responses even without automated control actions. In incentive-based DR programs, the customers are incentivized to respond through a separate compensation or incentive, such as a discount rate that is paid for their participation [16]. In these cases, the customer's resources are typically controlled automatically upon request offers and/or according to a contractual agreement [16]. From the utility point of view, incentive-based DR programs can be a very efficient option, as the contractual agreement obligates the customer to implement the requested DR actions. Thus, both approaches can enable efficient DR implementation, but their feasibility should be evaluated at a specific case by base basis. A second aspect is “Avoiding conflicts of interest”. For instance, the problematics of existing conflicting interests between electricity retailer and DSO are addressed in [17]. The DSO's objectives on DR are network-based, whereas the retailer's interest is market-based. If a customer's DR resources are used according to the retailer's market-based profit optimization needs, this can increase power peaks in distribution networks. On the other hand, if the customer's DR resources are used according to the DSO's needs to limit the peak powers in the distribution network, this can result in imbalance between the retailer's electricity procurements and sales (consumption). A third and final key aspect is the necessary modeling for the “Maximization of economic benefits”. This is not trivial, as DR benefits may depend on factors such as 1) Type of used DR resource; 2) Electricity prices and/or used pricing/incentive models; and 3) Adopted DR technology. The type of the DR resource defines also the resources availability and controllability, which impacts heavily on the attained economic benefits. In price-based DR actions, electricity-pricing mechanisms that appropriately reflect the costs of electricity procurement in wholesale markets, and the distribution tariff costs of the delivery are used to derive economic benefits. When that approach is not possible (for instance in situations taking into account electricity prices in real-time different wholesale markets), incentive based DR-models can be used, which enable the retailer’s direct control over customer-owned DR resources, and result in sharing of attained economic benefits between customer and retailer. Lastly, the adopted DR technical solutions, such as measurement, automation, control, and data transfer systems, each bear its own minimum requirements for allowed control response times, verification, etc., which dictates economics. For example, the use DR resources in the balancing power or reserve markets set higher requirements for real-time control and verification of control actions than the control of DR resources based on day-ahead (Elspot) market prices. Higher technical requirements increase implementation costs, but allows more flexible and multipurpose control of DR resources, thus providing higher potential revenue from DR, as demonstrated in [18]. In Finland, the currently widespread advanced meter reading (AMR) infrastructure enables hourly measurements and basic load control actions. Although the system does not operate fully in real-time, it provides a platform for implementation of basic DR actions, such as load control based on TOU tariffs, and verification of load controls in hourly markets.

III. DEMAND RESPONSE APPROACH

With the goal of more efficiently address the diverging interests between different market parties, the proposed comprehensive DR approach is a hybrid one, i.e. one that considers a combination of network and market-based DR schemes. Being customer-oriented, the approach prioritizes, at first, the network-based DR scheme, which facilitates electricity power delivery and the efficient use of the distribution network. The residual DR capacity not needed in the network-based DR scheme is then applied to the market-based DR, in order for economic benefits to be maximized.

A. Network-based Demand Response

Network-based DR schemes aim at facilitating efficient use of network infrastructure by decreasing peak loads, or preventing growth of those, at distribution level, thus assisting the DSO in minimizing operational and capital costs, and customers in minimizing their electricity bills. This is achieved through implementation of a power-based tariff, which provides incentive for customers to cut their peak power loads. Based on the DSO specific tariff setting analysis, a typical price of the power for a customer is 3 €/kW per month [19].

Network-based DR schemes can also assist the DSO in enhancing reliability of its operations, in minimizing network losses and in compensating for adverse impacts from RES integration [20].
B. Market-based Demand Response

The objective in market-based DR schemes, typically implemented by electricity retailers, is to maximize the economic benefits that the use of available DR resources in different electricity markets can provide. This can pertain to the minimization of electricity procurement costs, by controlling customers' loads based on the Elspot day-ahead market prices, as in the trading of aggregated DR resources in the balancing power and reserve markets. This work proposes the implementation of an incentive-based DR model, in which the electricity retailer controls directly the customers' loads, with the goal of maximizing economic benefits from their use in different electricity markets. To address this problem, the model proposed in [21], which is designed for the comprehensive use of DER under a context of electricity retailer’s short-term profit optimization in a variety of marketplaces, including day-ahead, intra-day, and reserve markets, is herein implemented.

IV. CASE STUDY RESULTS

The case analysis is carried out using real consumption data of 14 200 largely residential customers in an urban distribution network area in Southern Finland, outside temperatures, and historical electricity prices. The analyses are made within the one year time period in year 2013. The customer classification is based on predefined 29 customer groups of the DSO. Over 13 000 customers belong to a group of residential customers, of which 1 000 are electric space heating customers. The latter are selected as an example customer group to study the economic benefits provided by the proposed DR approach.

A. Load modeling and control constraints

Available hourly DR capacity, here the electric heating load, is analyzed by assuming that temperature dependent part of the consumption is electric space heating, and heating is needed only if the outdoor temperature is below +12°C. Methodology introduced in [17] is applied for dividing total load to heating (flexible) and other (non-flexible) loads, and to find out the heating load (i.e. DR capacity) during each hour. Hourly smart metering and outdoor temperature data within the examination period are used as input data. The load control potential is available for DR optimization from the autumn to the spring, and the highest load control potential is found to be located during the colder winter time. The modeled load control potential for the example customer group is illustrated in Fig 1.

Demand response typically includes a “payback effect”. In these analyses, it is assumed that loads are controlled off for one hour, and same amount of load is controlled on during next hour. Finally, in order to ensure customers' comfort (which is linked to indoor temperature) and to follow network regulations, the frequency and duration of the load control actions are constrained according to typical electric space heating customer requirements, defined as in [21].

B. Network-based DR optimization

The economic analysis of network-based DR optimization is based on the approach, that loads of a customer are reduced at the times of their peak powers in order to decrease, or avoid an increase, in network fee. Optimization here focus on the minimization of the customers’ network fee by decreasing their peak powers with the control of the heating loads, of which control potential is illustrated above. Customers are expected to decrease peak powers by 1, 2, 3 or 4 kW, as a result of the economic incentive provided by the power oriented pricing scheme. The results of the network-based DR optimization are summarized in TABLE I.

A price of 3.2 €/kW/month is obtained as the price that each customer pays for subscribed power capacity, assuming that the distribution tariff is entirely power-based. If other components, such as energy payments, are included in the distribution pricing, the price of power is going to change in relation to the weight of the power component in the distribution tariff. For example, if 50 % of the distribution tariff consists of the power component, the price of power is 1.6 €/kW per month, and the remaining 50 % consists of the energy payments.

<table>
<thead>
<tr>
<th>Weight of power component</th>
<th>Price of power per month [€/kW]</th>
<th>Economic benefit [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.32</td>
<td>3.880</td>
</tr>
<tr>
<td>0.2</td>
<td>0.65</td>
<td>7.760</td>
</tr>
<tr>
<td>0.3</td>
<td>0.97</td>
<td>11.650</td>
</tr>
<tr>
<td>0.4</td>
<td>1.29</td>
<td>15.530</td>
</tr>
<tr>
<td>0.5</td>
<td>1.62</td>
<td>19.410</td>
</tr>
<tr>
<td>0.6</td>
<td>1.94</td>
<td>23.290</td>
</tr>
<tr>
<td>0.7</td>
<td>2.26</td>
<td>27.180</td>
</tr>
<tr>
<td>0.8</td>
<td>2.59</td>
<td>31.060</td>
</tr>
<tr>
<td>0.9</td>
<td>2.91</td>
<td>34.940</td>
</tr>
<tr>
<td>1.0</td>
<td>3.24</td>
<td>38.820</td>
</tr>
</tbody>
</table>

The results show that the economic benefits from network-based DR increase linearly along with the weight of the power component and with the volume of peak load reduction. The benefits depend solely from price of power and volume of the peak load reduction. Possible energy payments to distribution pricing do not induce an impact, because the price and amount of energy is constant. The applied load control actions do not change volume of the consumed energy, rather shifting it.
forward in time. The highest economic benefits for the group of 1000 space heating customers, of around 39 000 € per kilowatt of load reduction, is obtained with 100 % power-based pricing.

C. Market-based DR optimization

In the economic analysis of market-based DR optimization, real hourly electricity consumption data of electric heating customers and historic market prices of the Nordic and national Finnish electricity markets, namely the day-ahead Elspot, balancing power and Frequency Containment Reserve for Disturbances (FCR-D) markets, were used in the simulation, with goal of shedding light over the profit-making potential provided by load control. In addition to simulation of the economic benefits from offering flexible loads to a single market, a daily market simulation has been computed to calculate the maximum profit-making potential provided by the comprehensive market-based DR optimization covering all the above-mentioned marketplaces.

The residual load control potential of the example customer group, which depend on the amount of the reduced peak loads illustrated in previous section, is applied for the market-based DR optimization. The simulations are made using an algorithm that calculates the profit-making potential from use of the available load control potential in the electricity markets at each hour, and that with given control constraints (available load control potential, and frequency and duration of control actions) optimizes load control actions for profit maximization to the retailer, see Eq. (1). Each applied control action results in a forward load shift. The controlled DR capacity is sold in a marketplace and accumulates profit for the retailer.

\[
\text{Max } \sum_{m \in \text{set of marketplaces included to the DR optimization}} \sum_{t=0}^{\text{duration}} \left( E_{\text{DR, opt}}(t) \times p_{\text{DR}}(t) + E_{\text{opt}}(t) \times p_{\text{opt}}(t) \right) \tag{1}
\]

Correspondingly, the payback effect of the load control takes place in the following hour and increases energy consumption. This energy needs to be purchased in a balancing market, which results in costs for the retailer. Considering practical business operation aspects to the retailer, it is assumed that in the case of Elspot, the payback energy is purchased in the Elspot market, whereas in the case of balancing power market, balancing trades cannot be accomplished anymore and the retailer hereby pays the imbalance power price for the energy. In case of FCR-D market, only the allocated capacity and hourly market prices define profits, as retailer’s possible energy imbalance, which is a result of FCR-D actions, is compensated by the TSO. The cost of the payback load is calculated by applying Eq. (2).

\[
C_{\text{pr}}(\tau^{'}) = \sum_{m} \left( E_{\text{DER, opt}}(\tau^{'}) \times p_{\text{DR}}(\tau^{'}) \right) 
\]

\[
E_{\text{DER, opt}}(\tau^{'}) \text{ change in the energy consumption in hour } \tau^{'}, \text{ as a result of the secondary effect of the DR action, applied at hour } \tau
\]

\[
p_{\text{DR}}(\tau^{'}) \text{ energy price in the balancing market in hour } \tau^{'}, \text{ as a result of the primary effect of the DR action, applied at hour } \tau
\]

The simulation results of the market-based DR optimization are illustrated in Fig 2.

![Fig 2. Simulation results: Economic benefits of market-based DR with relation to peak power reduction in network-based DR.](image)

The results show that within the whole set of simulations, the optimization of load control based on the Elspot market prices provides the lowest economic benefits, while the daily market simulation (optimal DR use in different market places) provides the highest economic benefits. The difference between the value offered by these two options is very substantial (approx. 15k€). The economic benefits offered by the balancing power market and FCR-D market options are very similar, being valued somewhere half way between the Elspot and daily market simulation cases. The increase in the volume of peak load reduction results in the decrease in the economic benefits of the market-based DR in all scenarios, but this impact is only moderate. Particularly, the rate at which the economic benefits decrease is higher with high peak load reductions (3 and 4 kW) than with lower peak load reductions.

Finally, the network and market-based DR results are put together for simplified visualization and summarized in Fig 3.

![Fig 3. Summary of network-and market-based DR simulation results.](image)

In Fig 3, dashed lines represent the economic benefits from network-based DR, in which the weight of the power-based pricing in the distribution tariff varies. The solid lines, in turn, illustrate the economic benefits provided by market-based DR optimization scenarios. The main conclusion from the plot is that the economic benefits from network-based DR increase...
much faster (especially if weight of the power-based pricing is high) than the economic benefits from market-based DR. Furthermore, if the amount of peak power reduction or weight of the power-based pricing increases from here on, the profitability of the network-based DR optimization increases compared to the market-based DR optimization. These results support the selected optimization approach, in which the network-based DR optimization was prioritized, while the residual DR capacity is used in market-based DR optimization.

V. FLEXIBLE GRIDS VISION

DR can be a significant source for improved operation of the electrical grid. However, it fits into a broader vision of flexible grids, which are enabled by a technological intersect between the energy and digital domains and user-centered approaches. If embraced, such vision may allow an even more efficient exploitation of DR’s potential, while in seamless integration with distributed energy resources (DER). In this vision, DER are interconnected through cloud services, so that all relevant market actors are provided with access to measurement and forecast data of the resources, and are able to send control signals to those resources, which they can control. The concept behind flexible grids is illustrated in Fig 4.

To put this vision into a testable, practical reality, the energy communities paradigm could be put into practice, by developing and implementing several interconnected building blocks so to form a system. Its elements could be divided into: A. Engagement of users, B. Development and implementation of relevant technologies, and C. Policy restructuring.

A. Engagement of customers and communities

To harness the full potential from distributed resources, customers need to be engaged to provide flexibility into the power system and the energy market. However, if flexibility resources are controlled at a single customer-basis to satisfy demands of wholesale markets, this may result in local network congestion, as illustrated in detail for instance in [22]. Hence, a community-scale approach needs to focus on synergies between different users. Furthermore, by developing relevant market models, seamless operation of the local and wholesale markets can be ensured. Innovative services are needed, to promote participation of end users and communities, and new kinds of business and ownership models, such as public-private partnerships, which ensure benefits of all stakeholders.

B. Enabling technologies

Relevant, able, and highly innovative technologies are a fundamental component to the flexible grids vision. Three important technological areas can be identified:

1) **Flexibility sources**, i.e. flexible loads and energy storage. In addition to developing storage and control technologies, interoperable automation and control systems are needed, which enable control of end user appliances and storage;

2) **Microgrid concept and technology** ensuring connections of DERs into microgrids, and seamless interoperation between microgrids and larger area distribution network;

3) **Secure and efficient communication infrastructure**, which enables transmitting real-time measurement information from individual devices and microgrids to market participants, and on-line control of these resources. Furthermore, it is necessary to ensure efficient interoperability by common information protocols, and address cybersecurity issues.

C. Empowering policies and market design

Policies and energy market design to enable novel business models need to modernize. Economic regulation of monopoly sector should be restructured so to provide incentives for DSOs to develop platforms for use of flexibility resources (e.g. energy storage) for grid purposes (e.g. the improvement of the capacity, reliability, and power quality) instead and besides of network reinforcements. Currently, regulation (e.g. in Finland) provides return for investments, but requires decreasing operational expenses, thus favoring network investments instead of use of flexibility services. The move towards RES generates greater access to low-cost sustainable energy, while demand for flexibility keeps increasing. In such context, the pricing based on the amount of the supplied energy with flat tariffs is far from optimal. Dynamic pricing in energy sales urges, in context of the grid as a “broadband network”, with price based on capacity (kW) reserved by each user from the grid. More, taxation could be dynamic, varying for instance with wholesale electricity price. To harness flexibility potential of different energy sources and build bridges between energy systems, a deeper interoperation of the electricity, heat, fuel, and gas markets is needed. Today, the state of liberalization and design varies significantly between these different markets.

D. Ongoing and Future research work

The flexible grid elements will be further developed in European and Finnish research projects, such as DOMINOES\(^1\), HEILA\(^2\), and DIGI-USER\(^3\). Furthermore, solutions are under testing in various pilot sites, such as LUT LVDC microgrid\(^4\).

VI. CONCLUSIONS

A new hybrid approach for maximization of DR benefits was presented that combines market and network-based DR.

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1 Smart Distribution Grid: a Market Driven Approach for the Next Generation of Advanced Operation Models and Services. Funded by EC, proposal 771066
2 Integrated business platform of distributed energy resources. Project funded by Tekes – the Finnish Funding Agency for Innovation
The aim is to facilitate large-scale DR that can generate benefits for the power systems, the electricity markets and society at large. Key aspects of comprehensive DR, customer response, conflicts of interest, and economics were overviewed. The validity of the approach was confirmed in a practical case with real-life market and consumption data from Finland. Results show that network-based DR benefits increase much faster than market-based DR benefits when load control potential is increased. This supports an approach that focuses primarily on network-based DR, using the residual load control potential for market-based DR.

In general, relevant peak loads are a rather rare occurrence. Hence, DR capacity is needed only occasionally for addressing peak power loads. This means that there can be plenty of available DR capacity after network DR optimization. The simulation results indicate that the use of this residual DR capacity for market-based DR optimization can provide significant economic benefits for the customer and retailer, thus increasing the overall benefits of DR. It is also seen that if the use of available DR capacity is optimized comprehensively, while considering the multiple opportunities provided by different electricity markets, significantly higher economic benefits can be achieved than by optimizing the use of DR resources in a single marketplace. The proposed DR approach bears potential for substantial economic benefits for participating market parties, i.e. retailers, DSOs, and customers. In addition, it could efficiently facilitate large-scale DR, thus improving the efficient operation of the power system and of the electricity markets in general, reducing the need for expensive and environmentally-adverse peak and balancing power production capacity, and compensating for the demand and price variations associated with integration of intermittent RES.

The broader vision of flexible grids was introduced, which may allow a more efficient exploitation of DR’s potential.

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