ANALYSIS OF DEMAND-RESPONSE PARTICIPATION STRATEGIES FOR CONGESTION MANAGEMENT IN AN ISLAND DISTRIBUTION NETWORK

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ABSTRACT

A novel approach compared to traditional grid expansion consists of using flexibility from demand-response resources to manage anticipated congestions. However, such an approach presents challenges as it requires both technical and economic considerations. This paper proposes and analyses two market-based strategies applied to detached houses for day-ahead congestion management. The strategies are implemented in an Ancillary Service Toolbox environment developed in previous work, and is applied to a real use case on Gotland, Sweden. The first strategy involves using a dynamic network tariff while the second uses spot price optimization. Simulations are performed for seasonal worst-case congestion scenarios while satisfying comfort and economic constraints of the DR participants.

Results show that while congestions are managed with a feasible number of participants, their savings are negligible for both strategies. The savings are 0.2-4.6 EUR/participant for the dynamic network tariff compared to 0-2.2 EUR/participant for the spot price optimization strategy. Moreover, results show that using a dynamic network tariff strategy implies a DSO cost in the range of 200-10200 EUR.

I. INTRODUCTION

The share of renewable energy in the electricity production is increasing and situations with a high penetration of intermittent renewables in distribution networks become more frequent. In the future this may require investments from Distribution System Operators (DSOs) to reinforce the grid in order to host the additional renewable capacity. The reinforcement may lead to an inefficient utilization of the grid, as renewable energy sources rarely produce at maximum installed capacity. Therefore, alternative methods to traditional network expansion such as congestion management might prove less costly and provide the possibility for network investment deferral. This study focuses on demonstrating the feasibility of using an Ancillary Service (AS) Toolbox concept for congestion management on an island facing power export challenges to an overlaying grid due to high local penetration of renewable energy sources. The toolbox uses primarily Demand-Response (DR) from space heating and domestic hot water consumption of detached houses to balance power during worst-case congestion scenarios. Congestions are managed by shifting space heating and domestic hot water loads to congestion hours while satisfying comfort constraints. The challenge arises during situations where high market prices concur with congestion events, leading to weak economic incentives for DR participation. The particular focus of this study is to propose and analyse market-based strategies for DR participation in the AS toolbox setting.

The island of Gotland in Sweden is chosen as a case study. Gotland can host up to 195 MW of rated wind power capacity. Above this limit the power transmission capacity of the HVDC cables connecting the island to the mainland is at risk of getting exceeded. Such a situation would endanger a safe and reliable operation of the power system.

II. BACKGROUND

II.1. AS toolbox concept

The AS toolbox concept was first introduced in paper [1] where its technical feasibility for the Gotland use-case was demonstrated. In brief, the AS toolbox consists of day- and hour-ahead DR provided by consumption flexibility from detached houses, a Battery Energy Storage System (BESS) handling forecasting errors from renewables and a curtailment scheme. The AS toolbox concept is illustrated in Fig. 1. The congestion problem was formulated as a linear optimization problem related to the scheduling of DR consumption:

Maximize	The sum of DR consumption from space heating and domestic hot water for all DR participants during hours of expected congestions
Subject to	Transmission capacity constraint Load shifting balance constraint Space heating constraints Domestic hot water constraints

The study was performed on four seasonal worst-case congestion scenarios concluding that at most 1600 day-ahead and 700 hour-ahead DR participants were sufficient to balance 5 MW wind power beyond the maximum hosting capacity on Gotland. Congestions were managed while satisfying participant comfort levels for indoor and hot water temperatures. One of the main limitations of the study was that it did not investigate how shifting loads impacts the electricity cost of the DR participant.

In this study we delimit ourselves to day-ahead scheduling of DR which accounts for most of the variation in consumption experienced by DR participants

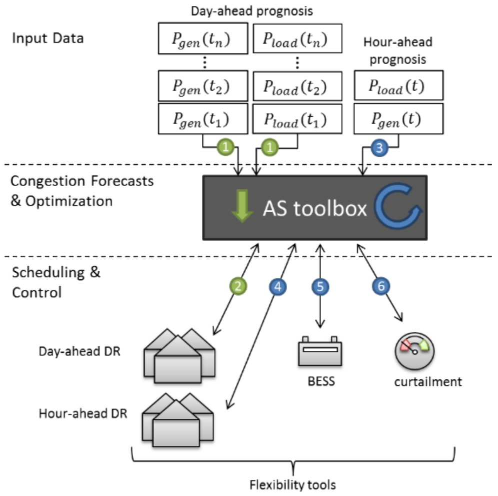

Figure 1. A conceptual overview of the AS toolbox describing the sequence of operation for congestion management. In steps 2 and 4, the number of DR participants is increased stepwise until the optimization problem is solved. [1]

II.2. The Swedish electricity bill

To understand how to develop market-based strategies for DR participants, it is necessary to know which parts of the electricity bill can be influenced. The average electricity bill composition for a household with electric heating in Sweden is presented in Fig. 2.

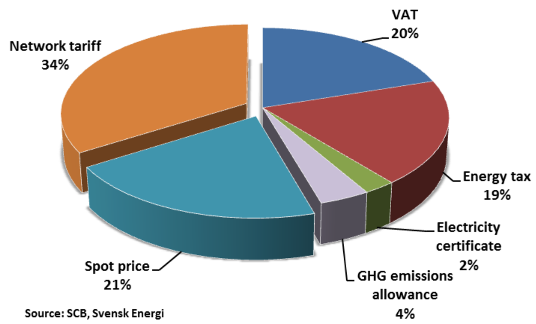

Figure 2. Average electricity bill composition (variable price contract) in July 2014 for a household with electric heating in Sweden. [2]

Since the 1st of July 2009, the Swedish electricity customers must be billed every month according to their actual consumption. [3]. The DSO reads the smart meter automatically every month and then sends the value to the customer's electricity retailer. Moreover, since the 1st of October 2012, the Swedish electricity customers can access their hourly consumption values without any extra charge. However, this applies only if the customer has a contract with a retailer which specifies that the electricity consumption is measured per hour. This measure allowed the introduction of new variable electricity contracts based on the hourly consumption and spot price. It gives the customer more flexibility and more possibilities to reduce its electricity bill by avoiding consuming when the spot price is high.

II.3. Related work

Depending on the scale of the project and the goals to reach, several ways of incentivizing the households to take part in DR have been proposed in the literature.

Norra Djurgårdsstaden [4] is a new sustainable area in Stockholm, Sweden. One of the project objectives is to shift a part of the household loads to off-peak hours. Two tests are planned in order to analyze the consumption of households receiving a combination of a price signal and a CO2 signal. The first proposed test is based on a varying electricity tariff in which the electricity cost component corresponds to the hourly spot price for the following day. The second test is not based on a tariff but on a signal varying according to the CO_2 emissions in Sweden. The tests have started but no conclusions are available yet. [5]

Study [6] investigates the impact of DR on the spot price in case of large scale DR participation. There are three scenarios with 10000, 100000 or 700000 participating households. The study considers an electricity tariff based on the spot price. It assesses the impact of the DR on the spot price and proposes a new market model including the DR in the spot price formation.

Finally, the ADDRESS project [7] also tackles the issue of incentivizing the DR participants. It recommends a "payment for monitored energy (decreased or increased)" [7]. Other strategies are proposed such as remuneration according to the number of hours when the smart appliances are connected to prevent overriding of DR or the introduction of a flexibility bonus when the DR is planned on the short term.

To conclude, market-based strategies for DR participation depend on the goals to reach. In the previous examples, the goal was to shift the loads to off-peak hours and a remuneration including a variable part proportional to the spot price is therefore recommended. However such remuneration would not be efficient if DR is intended for local congestion management. In the Gotland case study, hours of high wind power generation call for congestion management which do not necessarily correspond to hours of low spot prices.

III. MARKET-BASED STRATEGIES

Two market-based strategies were implemented as economic constraints in the AS toolbox setting and compared to a situation without DR. From the electricity bill composition (Fig. 2), one can see that an important part correspond to taxes and cannot be impacted. The hourly spot price cannot be modified, however consumption can be optimized according to hourly prices. Finally, the network tariff part corresponds to the DSO revenue. The network tariff is in general set to a fixed rate but can be modified under certain circumstances to help support the network. These two alternatives have been explored through the following strategies.

Strategy A: dynamic network tariff

Since DR scheduling is performed day-ahead and that the spot prices are also available on day-ahead, it is possible to offer the DR participants a dynamic network tariff: this tariff is calculated for each hour of the following day in order to compensate for the potential rise in the electricity bill induced by DR during the hour.
A reduced tariff cost would in this way be equivalent to a compensation paid by the DSO to the DR participant during the hours when DR induces an electricity cost increase. The optimization problem described in Section II.1. is first solved, and the hourly compensation per DR participant is later calculated in order to compensate for the potential cost increase according to Equation 1:

$$\boldsymbol{C(t) = \left(P_{heat}(t) + P_{boil}(t) - P_{heat,ref}(t) - P_{boil,ref}(t)\right) * \lambda(t)} \quad (1)$$

The hourly compensation $C(t)$ is equal to the consumption variation due to DR multiplied by the hourly spot price. Variables $P_{heat,ref}(t)$ and $P_{boil,ref}(t)$ denote the reference consumption of appliances without DR. $\lambda(t)$ denotes the hourly spot price. During the hours when the electricity cost is reduced thanks to DR, the cost reduction is considered as savings for the DR participant.
In this study, we assume that the DR participant has an hourly spot price contract. Yet this strategy can be used with any type of electricity contract. However, the DSO cost and DR participant savings would be different.

Strategy B: spot price optimization

Strategy B requires DR participants to have an hourly spot price contract. The cost constraint defined in Equation 2 is integrated in the optimization problem described in Section II.1.

$$\sum_{t=1}^{24}\left(P_{heat}(t) + P_{boil}(t)\right) * \lambda(t) \le \sum_{t=1}^{24}\left(P_{heat,ref}(t) + P_{boil,ref}(t)\right) * \lambda(t) \quad (2)$$

The cost constraint ensures that the daily electricity cost with DR is equal or lower than without DR. This allows to optimize the steering of appliances in order to solve the energy export problem while avoiding any cost increase for the DR participant.
Therefore the model will tend to increase the consumption during the hours of energy export problem and to decrease it during the hours when the spot price is high. The main advantage of this strategy is that when congestions are managed, no additional costs are required from the DSO. This strategy also induces in some cases savings for the DR participants.

IV. SIMULATION SETUP

The study is performed on the four seasonal worst-case congestion scenarios selected in [1].
The simulations have been carried out with the real hourly spot prices corresponding to the different scenarios. In addition, a high and low variation spot price profile were analysed to assess its influence on the results. These two spot price profiles are highlighted in Fig. 3.

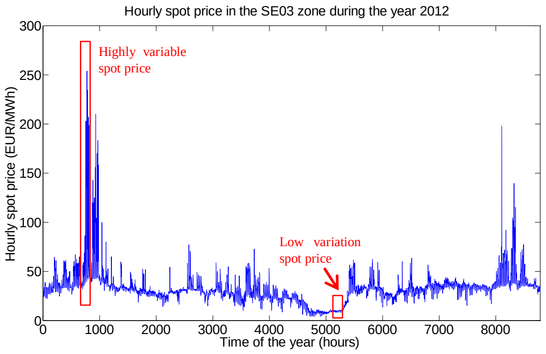

Figure 3. Hourly spot price data for the SE03 zone during the year 2012 [8]. The two spot price profiles selected for the sensitivity analysis are highlighted.

V. RESULTS AND ANALYSIS

Strategy A: dynamic network tariff

Required number of DR participants

Table 1 presents a summary of the number of required day-ahead DR participants for the seasonal scenarios simulated. The reader is referred to paper [1] for detailed information about the dynamics of the optimization problem.

	Number of required DR participants			
Scenario	**Spring**	**Summer**	**Autumn**	**Winter**
Day 1	1000	800	900	700
Day 2	900	700	900	1100
Day 3	1600	800	800	1400

Table 1. Required number of DR participants per day and seasonal scenario with strategy A to manage worst-case congestion events.

The results show that the largest number of day-ahead DR participants is required during the third day of the spring scenario, i.e., 1600 participants. The number of required DR participants does not dependent on the spot price profile since the DR scheduling is performed without cost constraint in the optimization problem.

Costs for the DSO and savings for the DR participant

Fig. 4 presents the results for the hourly electricity cost increase or decrease for the DR participant compared to a situation without DR. A positive value corresponds to a cost increase to be compensated by the DSO. The electricity cost increases during hours when the consumption with DR is greater than it would have been without DR. A negative value corresponds to a cost decrease, considered as savings for the DR participant.

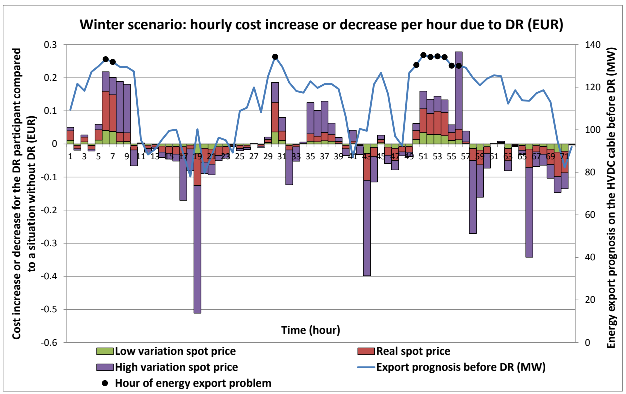

Figure 4. Hourly cost increase/decrease for the DR participant for various spot price profiles (winter scenario). The cost increases are compensated by the DSO.

It can be noted in Fig. 4 that the hours of energy export problem correspond to hours when the compensation paid by the DSO is high. The reason is that the AS toolbox aims at maximizing the consumption during these hours in order to solve the energy export problem. It can also be seen that the spot price has a considerable impact on the cost increase or decrease: the mean hourly compensation is about 10 times higher with high variation spot prices than with low variation spot prices. Tables 2 and 3 show the total compensation and savings for the different scenarios and confirm this observation.

	Total compensation paid by the DSO to the DR participants (EUR)		
	Low spot	**Real spot**	**High spot**
Spring	862	3186	10225
Summer	200	210	1376
Autumn	410	1225	4183
Winter	525	1869	3843

Table 2. Total compensation paid by the DSO per seasonal scenario and spot price profile (for 3 consecutive days).

	Total savings per DR participant (EUR)		
	Low spot	**Real spot**	**High spot**
Spring	0.5228	1.8742	4.5602
Summer	0.2444	0.2607	2.2988
Autumn	0.4453	1.5069	4.2933
Winter	0.3825	1.4771	3.8343

Table 3. Total savings per DR participant, seasonal scenario and spot price profile (for 3 consecutive days).

One should note that the total savings for the DR participants are not equal to the compensation paid by the DSO. This is due to the fact that the spot price is varying hourly and shifting a load can therefore modify its cost. The results show that the highest compensation, reaching about 10200 EUR, occurs during the spring scenario for a high variation spot price profile.

Strategy B: optimization with the spot price

Required number of DR participants

Table 4 presents a summary of the number of required day-ahead DR participants for the seasonal scenarios simulated. It corresponds to the highest number of required DR participants among the three days of each scenario.

	Max number of required DR participants		
	Low spot	**Real spot**	**High spot**
Spring	2600	Unsolvable	Unsolvable
Summer	800	800	800
Autumn	900	900	1000
Winter	1400	1400	1400

Table 4. Max required number of DR participants per seasonal scenario and spot price profile with strategy B to manage worst-case congestion events.

First it is noted that adding a cost constraint (Eq. 2) in the optimization problem barely increases the number of required DR participants for the summer, autumn and winter scenarios. Changing of spot price profile also has a rather limited impact on the number of required DR participants. The only increase, of 100 additional DR participants, is observed for the winter scenario combined with a high variation spot price profile.
However, the addition of the cost constraint makes the problem unsolvable for the spring scenario. It means that it is not possible to simultaneously solve the energy export problem and reduce the cost of the participants. This is due to the characteristics of the congestion profile and the limited flexibility of the appliances for that particular scenario. The DSO will have to compensate the DR participant in this case. There is an exception in case of low variation spot price profile: the problem is solvable but it requires 2600 DR participants which is very high compared to the other scenarios. In this configuration it may be more beneficial for the DSO to further compensate than to increase the size of the DR pool.

Savings for the DR participant

The savings for the DR participant are summarized in Table 5.

	Total savings per DR participant (EUR)		
	Low spot	**Real spot**	**High spot**
Spring	0.0002	-	-
Summer	0.0006	0.0058	0.8989
Autumn	0.0057	0.1553	1.2121
Winter	0.0126	0.1530	2.1680

Table 5. Total savings per DR participant, seasonal scenario and spot price profile (3-days simulation).

For all scenarios and spot price profiles, the savings are below 2.2 EUR which is extremely low. The cost constraint in the optimization problem does however ensure that DR participants are not being penalized.

VI. DISCUSSION

Interpretation of use case results

It is important to note that the use case results should be interpreted as results from worst case conditions. The results on required number of DR participants ranged from 800 to 1600 day-ahead participants for both strategies. We can therefore conclude that the introduction of market-based constraints does not significantly influence the number of required DR participants. There is one exception, the spring scenario, which cannot be solved with strategy B.

Moreover, whatever the strategy chosen, the savings made by the DR participant are extremely low and do not constitute a real incentive to take part in DR. However, both strategies allow the introduction of DR without any cost rise for the detached houses participating.

The main advantage of the dynamic network tariff strategy is that it works with any type of electricity contract. The use case chosen in this study involves an hourly spot price contract but this is not a requirement. It was shown that the total compensation paid by the DSO is very dependent on the spot price profile.

On the other hand, strategy B requires the DR participant to have an hourly spot price contract. The main advantage of strategy B is that it is almost always possible to manage the congestion problem without any additional costs for the DSO.

Use case limitations

The use case has inherent limitations that the reader should be aware of. The AS toolbox and seasonal worst case scenarios limitations are detailed in [1]. Moreover, the wind power production prognosis errors are not taken into account in the analysis. These could lead to additional costs for the DSO in case wind curtailment is required to compensate for wind power production being higher than expected.

VII. CONCLUSIONS

In this paper market-based strategies for DR participation of detached houses were proposed, integrated in an AS toolbox and analysed. The first strategy consisted of a dynamic network tariff for which the rate is reduced during hours of increased electricity cost induced by load shifting. The second strategy optimized the DR scheduling in order to manage congestion problems while reducing the daily electricity bill of the DR participant by harnessing hourly variations in spot price. Both approaches were simulated for a real use case facing energy export problems due to high penetration of local wind power. The simulation results demonstrated the feasibility of an AS toolbox including economic constraints. Seasonal variations mostly due to different production and consumption patterns were observed, as well as variations induced by different spot price profiles. The simulations showed that the DSO will pay a total compensation of at most 10225 EUR with strategy A for the use-case. Strategy B is at no cost for the DSO but may present some limitations for day-ahead congestion management. Both strategies applied to the use-case presented negligible savings for the DR participants (0-5 EUR/participant). However, end-user savings will increase if DR is required more frequently during the year. For the use-case, congestion events are unlikely, but other type of ancillary services such as voltage regulation could potentially generate more savings for end-users.

In future work, the market-based strategies will be evaluated for other types of ancillary services. A sensitivity analysis will be carried out to assess the impact of production prognosis errors on the results. Finally, a cost benefit analysis will be conducted on the AS toolbox approach versus traditional grid expansion.

Acknowledgements

Study performed in collaboration with Vattenfall R&D and KTH as part of the Smart Grid Gotland Project.

REFERENCES

[1] D.A. Brodén, C. Sandels, and L. Nordström, 2015, "Assessment of Congestion Management Potential in Distribution Networks using DR and Battery Energy Storage ", *Proceedings ISGT 2015 conference*.

[2] Svensk Energi, 2014, "Diagram och tabeller konsument elpriser och elskatter i Sverige och Norden.". [Online]. Available: http://www.svenskenergi.se/Global/Statistik/Diagram-och-tabeller-konsument-elpriser-och-elskatter-i-Sverige-och-Norden.pdf. [Accessed 23-10-2014].

[3] K. Widegren, Director Swedish Coordination Council for Smart Grid, 04-09-2012, "Smart Grid and Smart Metering - Swedish Experiences", *EEA webinar*. [Online]. Available: http://ew.eea.europa.eu/eea_energy/webinar-material/presentations/webinar-smart-meters-final.pptx. [Accessed 09-01-2015].

[4] C. Bergerland, K. Faber, and O. Hansson, 2011, "Norra Djurgårdsstaden. Nya marknadsmodeller för engagerade kunder", Elforsk rapport 11:66.

[5] NyTeknik, 05-04-2013, "De är testpiloter för nya smarta elnätet". [Online]. Available: http://www.nyteknik.se/nyheter/energi_miljo/energi/article3666235.ece#comments. [Accessed 11-19-2014].

[6] L. H Rasmussen, C. Bang, and M. Togeby (READY project), 2012, "Managing congestion in distribution grids. Market design consideration.", Ea Energy Analyses, Denmark.

[7] V Alagna et al, 2011, "Deliverable 5.1 - Description of market mechanisms (regulations, economic incentives and contract structures) which enable active demand participation in the power system.", ADDRESS project.

[8] Nord Pool Spot, "Elspot Prices_2012_SEK". [Online]. Available: http://www.nordpoolspot.com/historical-market-data. [Accessed 14-10-2014].