

Integrating an agent-aggregator model for demand side management in distribution network planning

Citation for published version (APA):

Dukovska, I., Bernardis, R., Morren, J., & Slootweg, H. (2018). Integrating an agent-aggregator model for demand side management in distribution network planning. In *Proceedings of the 2018 CIREN Workshop on Microgrids and Local Energy Communities* Article 0320

Document license:

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Document status and date:

Published: 01/06/2018

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
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INTEGRATING AN AGENT-AGGREGATOR MODEL FOR DEMAND SIDE MANAGEMENT IN DISTRIBUTION NETWORK PLANNING

Irena DUKOVSKA
TU Eindhoven
The Netherlands
i.dukovska@tue.nl

Raoul BERNARDS
Enexis B.V. &
TU Eindhoven
The Netherlands
raoul.bernards@enexis.nl

Johan MORREN
Enexis B.V. &
TU Eindhoven
The Netherlands
johan.morren@enexis.nl

Han (J.G.) SLOOTWEG
Enexis B.V. &
TU Eindhoven
The Netherlands
han.slootweg@enexis.nl

ABSTRACT

This paper investigates the feasibility of demand side management (DSM) services as an alternative to grid reinforcements in the long-term planning of low voltage (LV) distribution networks. For this purpose, a market based approach for DSM is used and three alternative market based strategies are considered. The distribution system operator (DSO) can procure flexibility differently in each strategy. Hierarchical Multi-Agent System (MAS) is used as the modeling approach for the network and the entities included. The market strategies are applied to existing Dutch LV network for several future load scenarios.

INTRODUCTION

In recent years, an increasing number of distributed energy resources (DERs) is being introduced in the low voltage (LV) electrical grid, such as solar PV, micro-CHPs and electric vehicles (EV) [1]. Until now, the DERs are mostly accommodated in the LV distribution in a so called “fit-and-forget” approach [2]. This might result in a number of problems such as thermal overloadings and under-/over-voltages even in the current operation of the grids [3]. The number of installed DER is expected to continue to grow in the future [1] [2]. Hence, the future distribution networks should be able to cope with these developments. The traditional manner of planning the grids resolves network congestions with grid reinforcements which might become inadequate and cost-ineffective approach. Therefore, distribution system operators (DSOs) should consider other planning alternatives such as deploying Demand Side Management (DSM) [2].

In this paper, a market based approach for DSM was selected in accordance to the legislative trends that foster market procurement of additional grid services and user centricity [4]. The impact of three different DSM strategies is evaluated in order to incorporate it in the planning process for distribution networks. The methodology and the strategies are explained in the following section. Next, the results of a case study for an existing Dutch LV network are presented and discussed. Finally, conclusions and remarks are given.

METHODOLOGY

MAS aggregator model

Implementation of DSM methods in a smart grid requires participation of multiple entities in the network. Multi-Agent System (MAS) represent a suitable technology to model and simulate the distributed nature of electrical power networks. A MAS is a system comprised of two or more agents that interact with each other and the external environment in order to achieve some objective or reproduce some behavior [5]. Agents can represent physical components of the grid (e.g. feeder agent, smart-appliance agent) but there can also be agents representing other functionalities (such as a DSO agent).

The MAS used in this paper is based on the PowerMatcher technology, developed by FlexiblePower Alliance Network (FAN) from the Netherlands, for matching electricity supply and demand [6]. All household appliances are represented by an agent. They communicate their power demand to the household agent which aggregates their demands. This represents the first level of aggregation in the MAS model. The second level of aggregation is on feeder level where the demands from all households in that feeder are aggregated. Finally, at a MV/LV substation, the third and final aggregation is done. The MAS model is presented in Figure 1.

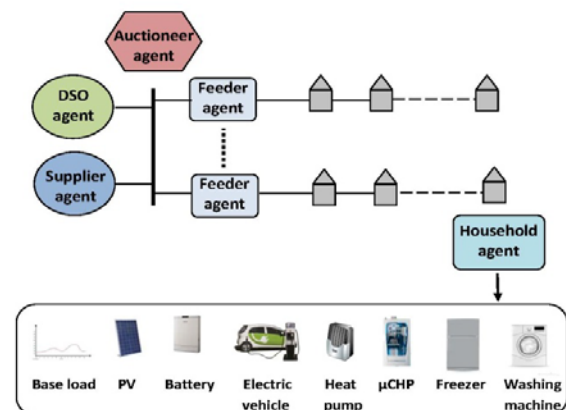


Figure 1 MAS aggregator model structure

Market-based DSM strategies

The inclusion of DERs in the market is based on the microeconomic principles of equilibrium market.

Depending on the way the DSO procures flexibility services from the end users, three different strategies are developed and presented below. In addition, a no-market strategy is simulated as a base case.

Free market strategy

In this strategy, the main goal of the market operation is to balance real-time power matching and thus maximizing social welfare within the market. Each household device agent expresses its momentary demand function as a bid $d(\lambda)$, stating its willingness to pay, i.e. the amount of power the agent wants to consume (or produce) at a given price λ . Production is represented as negative consumption. All bids are aggregated by the auctioneer agent where the equilibrium price is determined and communicated back to each device. The prices are given in per unit values from 0 to 1 with resolution of 1 step and thus they represent control signals. The equilibrium price λ^* is determined by equation 1 [7]:

$$\sum_{a=1}^{N_a} d_a(\lambda^*) = 0 \quad (1)$$

where N_a is the total number of device agents and $d_a(\lambda)$ is the demand function of agent a .

This strategy does not consider the technical limitations of the grid, such as thermal limits of components or voltage levels, only economic preferences. Power consuming devices wish to minimize their costs by consuming when prices are low whereas power producing devices wish to maximize their profit by producing more when prices are high. All device agents are led by these principles. The practical implementation of the market organization and the roles and responsibilities of the involved stakeholders is outside the scope of this work. However, it is considered that regardless of the actual market implementation, the participants would be led by profit maximizing or cost-saving principles. Thus, the effect on only economy driven market setups on the network can be evaluated.

Grid constrained market strategy

In this strategy, power trading is done as in the previous strategy with the addition that network constraints must be maintained. This is done through the DSO participation in the market implemented through the functionalities of the feeder and the DSO agent. If an overload occurs in the Free market strategy, there is need for the DSO to participate and move the market equilibrium point. This is done by issuing an additional demand bid that increases the market price, resulting in decreasing the consumption and/or increasing the local production. However, in the moments of congestions the actions from the DSO agent have limited impact and may not resolve the problems.

Therefore, the DSO agent has another functionality, to prevent overload in the first place, by shifting demand

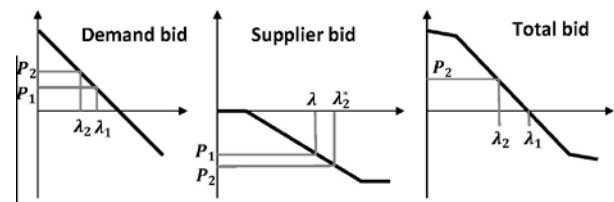


Figure 2 Technical coordination of the DSO agent

to the intervals before an overload occurs. The technical coordination is presented on Figure 2. After the daily aggregation of the demand and supplier bids, the equilibrium price λ_1 is determined for each interval with the corresponding power demand P_1 . The DSO agent evaluates then if more power P_2 can be consumed in each moment by revising the bid curve. If so, the corresponding lower price λ_2 is communicated back to the customers. In order to cover the extra demand, a new higher price λ_2^* is sent to the supplier agent. In this way, the DSO stimulates certain behavior from the other market agents but does not enforce it [8].

Direct grid control strategy

As opposed to the indirect price-based strategies proposed previously, this control strategy enables the DSO to directly control the demand of consumers. In normal operating regime, the system operates under market based method as in the Free market strategy. However, when the total loading of the MV/LV transformer is surpassed, the DSO undertakes actions to curtail load to resolve the congestion. The curtailed load should be large enough to maintain the load under the transformer maximal rating, as given in Equation 2 [3]:

$$P_{cur} \geq |d_{auct}(\lambda)| - |P_{tr,nom}| \quad (2)$$

where P_{cur} is the power that is curtailed, $d_{auct}(\lambda)$ is the aggregated bid at auctioneer level and $P_{tr,nom}$ is the nominal transformer power.

From DSO perspective, load curtailment is an undesirable action because it affects the reliability of supply and has a negative effect on the company image. Therefore, if load curtailment actions are to be undertaken, a goal for the DSO is to minimize the number of customers affected by such action.

Future load scenarios

To evaluate the impact of different penetrations of various DER and their impact on the distribution grid, a scenario-based modelling approach can be used as in [1]. Three distinct scenarios in terms of production and consumption are defined to encapsulate the complexity and uncertainty regarding the integration and operation of DERs in the LV grid. Thus, a wide range of combinations of DER is covered in a way that their most prominent characteristic will be emphasized and dominant in the given scenario. This would lead to a concrete effect on the grid that can be attributed to the DERs included in that scenario. The defined scenarios are presented in Table 1.

Table 1 Future load scenarios

	1 - High level demand (%)	2 - High level production (%)	3 - Mixed level production and demand (%)
EV	40 – 60	40 – 60	100
HP	100	0	50
μ-CHP	0	100	50
PV	40 – 60	40 – 60	100

CASE STUDY AND RESULTS

Network overview

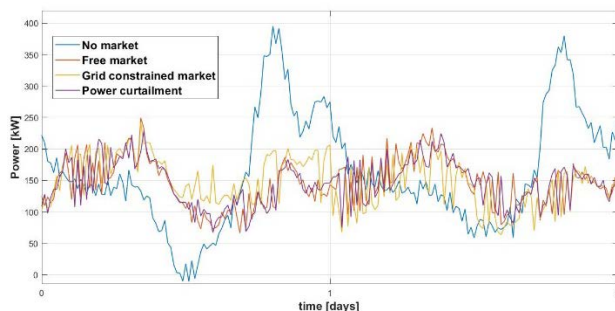
The proposed market strategies are applied to an existing Dutch LV network, representing a typical rural grid. The grid is connected to the MV network through a 10.5/0.42 kV, 250 kVA distribution transformer and has a radial topology with five underground feeders. The connected load is residential and there are 181 households of different types [9].

The grid and the MAS are both modelled and simulated by using Matlab programming language. Load flow calculation is performed by using self-developed backward/forward sweep algorithm, suitable for radial networks, as presented in [10]. A balanced distribution of the households' connections over the three phases is assumed.

Weather data (temperature and solar radiation) are collected from the database of the Royal Dutch Meteorological Institute (KNMI) [11]. Annual energy profiles for the household base load are used in accordance to the average yearly consumption per household type as identified in [9]. Measurements of electric vehicle power consumption taken from public charging stations are used. The data is reviewed to only keep those that correspond to in-home charging profiles. The demand functions of the device agents are modelled based on [6] and [7].

Test results

Annual simulation is performed for the different market strategies and future load scenarios with resolution of 15 minute intervals. For every interval, the market clearing takes place after which a power flow calculation is done. An example is presented in Figure 3.


Figure 3 Power flow for two days (S3)
Table 2 Results for the test network – reduction compared to the base case (ΔP_p – power peak reduction, $\Delta t_{o,av}$ – reduction of average duration of overloading, ΔE_i – reduction of energy imported from the MV grid)

	Free market			Grid constrained market			Direct grid control		
	ΔP_p %	$\Delta t_{o,av}$ %	ΔE_i %	ΔP_p %	$\Delta t_{o,av}$ %	ΔE_i %	ΔP_p %	$\Delta t_{o,av}$ %	ΔE_i %
S1	1	50	6	-7	66	6	42	52	8
S2	45	100	15	/	/	/	/	/	/
S3	35	63	17	39	68	16	47	70	17

The most relevant parameters for network planning for each market strategy in comparison to the base strategy (no market) are presented in Table 2. The introduction of a local market improves the operation of the network and there is notable power peak reduction (ΔP_{peak}). In the scenario with high level of local generation (S2), it is even sufficient to resolve the network issues and there is no need for additional measures from the DSO. When mixed level of local production and demand is present in the network (S3), participation of the DSO in the market leads to larger reductions in the peak power reduction and the average duration of the noted transformer overloadings ($\Delta t_{ov,av}$). As expected, direct curtailment control on behalf of the DSO would lead to even higher reductions compared to the other market strategies and the base case.

However, the network congestions cannot be resolved through DSM in every case. In the scenario with high level of demand (S1), due to the large load, there is limited amount of flexibility. Hence, the actions of the DSO to shift or decrease the demand may lead to even higher power peaks. Nevertheless, the average duration of the transformer overloadings ($\Delta t_{ov,av}$) is reduced, which considering the cyclic loading pattern of MV/LV transformers in residential areas can withstand the occurrence of such peaks [1].

In general, the implementation of a local electricity market, encourages the consumption of decentralized generated power. Thus, the imported electricity from the supplier through the transformer (ΔE_{imp}) is reduced in all cases. Next, the maximal loadings in the individual feeders and the highest and lowest voltage levels are noted and there are no violations of the limits in any of the cases.

Cost benefit analysis

To consider DSM as a planning alternative, the costs related to the implementation and the operation of such management systems should be evaluated. Ideally, the costs for DSM implementation should not be greater than the savings achieved by deferring investments. To be able to compare the costs, the per-unit price of the simulation model is transformed into a monetary value. It is assumed that the medium value of the per-unit price vector is equal to the electricity price that households

Table 3 Cost benefit analysis (C_{loss} – annual DSO costs for technical losses, C_{DSM} – annual DSO costs for related to DSM, $C_{S,tot}$ – total annual societal costs, sum of the DSO costs and the consumers' costs)

	S1 – High level of demand			S2 – High level of production			S3 – Mixed level of production and demand		
	C_{loss} [€]	C_{DSM} [€]	$C_{S,tot}$ [€]	C_{loss} [€]	C_{DSM} [€]	$C_{S,tot}$ [€]	C_{loss} [€]	C_{DSM} [€]	$C_{S,tot}$ [€]
Base case	3,108	0	271,362	2,613	0	132,088	3,159	0	222,329
Free market	2,983	0	388,355	2,204	0	107,563	2,629	0	234,599
Grid constr.	3,043	358	396,691	/	/	/	2,587	4,909	231,212
Direct control	2,677	8,719	390,536	/	/	/	2,499	47	234,466

pay in the Netherlands, including taxes. The same value conversion is made for all load scenarios and market strategies. The price used for the value conversion is 0.18 €/kWh and is the price that customers pay in the base case scenario [12].

The operational costs for the DSO consist of the costs for technical losses and costs for applying DSM, either through market participation or direct grid control. In the former, the DSO pays for the price difference in shifting the market equilibrium. In the latter, it compensates the consumers for the curtailment at the actual price. The annual electricity costs for all consumers are calculated. The results are presented in Table 3.

For the DSO, each market strategy results in reduction of losses in the cables and the transformer (C_{loss}), thus lowering the DSO costs in Free market strategy. However, DSM actions lead to additional costs (C_{DSM}) for the DSO in the other two strategies. Which strategy is more cost-effective for the DSO depends on the load scenario, as can be seen for S1 and S3 in Table 3. Another comparison of these two market strategy versus the Free market strategy raises the question whether the savings in losses outweigh the additional costs related to DSM. To implement DSM as an alternative in network planning, the savings from reduction of technical losses and the additional costs for DSM should be compared to the grid reinforcement alternative.

For the customers, variable prices could lead to higher electricity costs, resulting in higher total societal costs ($C_{S,tot}$). However, not having a market would require additional investments from the DSO which would be socialized and translated into increased tariff costs for the customers. Therefore, the cost savings from avoiding such an investment might outweigh the increased electricity price in a market based strategy, maximizing the social benefit.

CONCLUSIONS

In this study, a method to implement DSM as an alternative in LV distribution network planning is presented. Three different market based DSM strategies are developed and three future load scenarios are

considered. The results of the case study show that implementing a market-based strategy reduces the impact that future penetration of DERs would have on the peak load and the losses in the existing infrastructure of the distribution system, compared to an uncoordinated approach. Further procurement of flexibility services by the DSO can additionally improve the operation of networks. Based on the cost benefit analysis there are savings due to the reduction in technical losses but additional costs for deploying DSM. Lastly, the viability of DSM as an alternative in network planning is also highly dependent on the regulatory framework and the assigned roles and responsibilities to different parties, including the DSO.

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