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Published in:
Proceedings of 2017 IEEE Power & Energy Society General Meeting

DOI (link to publication from Publisher):
10.1109/PESGM.2017.8274224

Publication date:
2017

Document Version
Accepted author manuscript, peer reviewed version

Impact of Demand Side Management in Active Distribution Networks

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***Abstract*—Demand Side Management (DSM) is an efficient flexible program which helps distribution network operators to meet the future critical peak demand. It is executed in cases of not only technical issues like voltage sag or swell, transformer burdening, cable congestions, but also to increase the degree of visibility in the electricity markets. The aim of this paper is to find the optimal flexible demands that can be shifted to another time in order to operate the active distribution system within secure operating limits. A simple mechanism is proposed for finding the flexibility of the loads where electric vehicle, electric heating etc. are present. Simulations are carried out in Danish low voltage grid for summer and winter cases.**

I. Introduction

Renewable Energy Sources (RES) like wind, solar PV etc., are increasingly deployed into the MV/LV distribution grid either utility owned or customer owned, and poses many challenges in the planning and operation of the network. Demand Side Management (DSM) is used for the effective response of flexible loads with respect to changes in electricity pricing, where, either there are incentives for reducing consumption or network security is endangered [1]. A survey on the various DSM techniques that can be implemented on residential loads is presented in [2].

The Demand Response (DR) can be achieved either by reduction of the consumption during high demand periods which may result in loss of comfort [3], or shifting the demands with respect to high electricity prices by loads such as Heat Pumps (HP), Electric Vehicle (EV) etc. but not for industrial customers where rescheduling incurs huge cost, or customers with onsite-generation with distributed generation [4]. Some customers might be able to increase their total energy consumption without having to pay more money by operating during off-peak periods. Depending upon the present electricity market architecture, Distribution Network Operator (DSO) buys the electricity and do not have much access about the flexibility of individual customers [5], [6]. But, in order to apply DR, the DSO have to estimate the underlying flexibility in the distribution network. The flexibility data is available with Balance Response Party (BRP) also called as Aggregators. These BRPs contains the information about the aggregated power measurement at the point of connection of the grid and the consumers. Moreover, device level flexibility information gives much better control in a DR program [7], [8].

This paper discusses the technical challenges that can be faced by a DSO where the distribution network contains solar and wind, domestic installations, and also flexible loads with more EVs and Electric Heating (EH) loads. It is considered here that the DSO also plays the role of an aggregator. The job of an aggregator is to collect the information about the flexibility of the customers that can be subjected to shifting, here in this study, DSO is considered to play the role of an aggregator also. A simple optimal solution is proposed for finding the aggregated flexible demand or flex-offer that can be offered by the flexible loads present in the distribution network. Two cases are considered, summer case and winter case.

The paper is organized as follows. In Section II methodology is explained with the help of optimization formulation subjected to constraints for finding the aggregated flexibility of loads. In Section III, two case studies are described for the given solar, wind, EV and EH profiles for which the results are also presented. Finally, discussions in Section IV and conclusions in Section V.

II. Methodology

The main objective of the DR is to reduce the peak demand and operation cost. Mainly DR techniques can be classified into two types: incentive-based and price-based [9]. In direct load control programs, utilities have the ability to remotely shut down participant equipment including air conditioners on a short notice. This kind of programs is mainly executed at residential customers and small commercial customers. Utilities are offering a wide range of DR schemes and tariffs [10], [11], [12] that have been settled to use the available energy more efficiently and to encourage customer response and competitive energy retailers.

A non-linear optimization is formulated and given in (1), for finding the aggregated flex-offers over a given time horizon for the following constraints: power balance, thermal limits and voltage limits.

The formulation is as follows:

Minimize $\Delta V_{mt}/\Delta P_t$

subject to

$$\begin{aligned}
&P_i = \sum_{q=1}^{n} V_i V_q Y_{iq} cos(\delta_i - \delta_q - \theta_{iq}) \\
&Q_i = \sum_{q=1}^{n} V_i V_q Y_{iq} sin(\delta_i - \delta_q - \theta_{iq}) \\
&V_{min} \leq V_i \leq V_{max} \\
&S_l \leq S_l^{rated}
\end{aligned} \tag{1}$$

where, ΔV_{mt} is the change in distribution system minimum voltage at time t; ΔP_t is the change in power demand at time

t; P_i, Q_i are the real and reactive power injections at node i; V_i, V_q are the voltages at node i and q. Y_{iq} is the iq^{th} element of the admittance matrix; δ_i, δ_q are the phase angles of complex voltages at i^{th} and q^{th} nodes, respectively; θ_{iq} is the phase angle of admittance matrix iq^{th} element; V_{min}, V_{max} are the lower and upper limits on the voltage; S_l is the thermal limits of l^{th} feeder; $S_l{}^{rated}$is the maximum thermal capacity of the l^{th} feeder.

A methodology for shifting the aggregated flexible demand called as 'Flex-offers' [13] with respect to time (either to next hour or day) is proposed for the secured operation of the distribution networks. The term 'Flex-offers' are defined as the power measurements corresponds to the flexible devices that are shifted to the next hour/day in a week. The working principle of the proposed method is shown with help of flowchart in Fig. 1. The proposed algorithm finds the suitable timings for EVs charging and switching ON of heating loads subjected to the distribution network operating constraints.

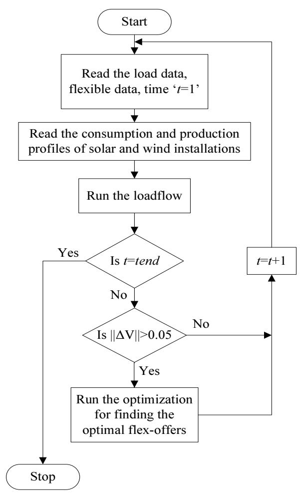

Fig. 1. Flowchart of the methodology

III. Case Studies

A Danish Low voltage grid is considered for all the studies presented here. The single line diagram of the distribution system is shown in Fig. 2. The parameters like cable ratings, line data and transformer that are used for modelling the system are considered from [14]. The loads including flexible loads, solar and wind, are modelled as constant power loads. A 315 kVA off-load tap changing transformer is used and 1 p.u. is assumed on the transformer secondary side.

The grid is shown with heat-map of voltage levels. The coloring shows the light green, green, darkgreen and red as ($<$ 1.05 and $>$1), ($<$ 1 and $>$0.98),($<$0.98 and $>$0.95) and ($<$0.95), respectively. This voltage level heat-map shown is same for both the summer and winter cases with considered loads. The information about the load units is given in Table I. Installation capacities of solar and wind, domestic customers are given in Table II. The data rate is 15 min interval.

- The real time data for both the consumption and production profiles of the households with the solar and wind installations are available. The production profiles of both the wind and solar are not the actual productions, but the extra production that is sent into the grid after meeting the demand at the point of location.
- According to Danish grid code requirements, rapid voltage changes should not exceed +/- 5 % [15]. However, changes up to +/-10% is, acceptable for a few times a day. The operational limits that are considered for voltage are +/- 5 %.
- The loads with the solar, wind, EVs and EH are randomly distributed all over the network.

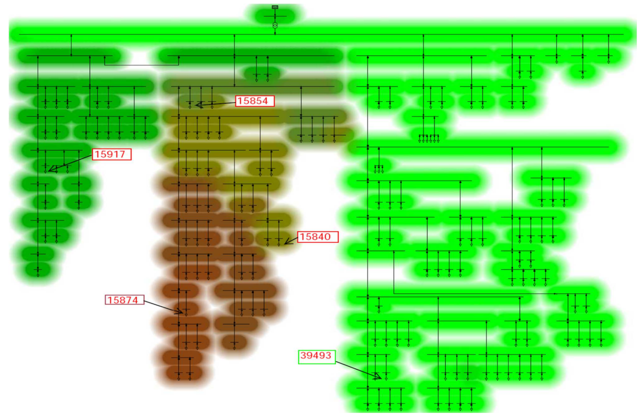

Fig. 2. DIgSILENT model of distribution network.

TABLE I
LOAD INFORMATION

Load type	**Total**
Domestic loads	103
Domestic+EH loads	11
Agricultural loads	9
Commercial loads	6
Industrial loads	1
Mixed loads	1
Unknown loads	2
	133

TABLE II
INSTALLATION CAPACITIES OF SOLAR, WIND AND FLEXIBLE LOADS

Installations	**Units**	**Capacity**
Solar	36	2-20 kW
Wind	67	6-32 kW
Flexible loads	**Units**	**Capacity**
EV	32	3.75 kW
Heating loads	32	2 kW

Real time data is available for April week in 2016 for four households containing the flexible loads. The consumption profiles of the available four flexible loads are shown in Fig. 3, and the same data is used for 8 times to make 32 flexible loads. The capacities of flexible devices that are present are given in

Table II, which is used in the optimization for finding the flex-offer of individual customer. Table II gives the information about the flexible devices i.e., EV capacity of 3.75 kW and heating loads of 2 kW which are present and they are willing to shift their consumption timings. The aggregated flexible demand that can be shifted with respect to time which are offered by the flexible loads for a week is illustrated in Fig 4. This information is available with aggregators/DSO. This aggregated power measurement corresponds to all the available flexible loads with respect to the time. For both the Figs. 3 & 4, same color coding is used in order to show the flexibility at each load. For instance, it can be observed that flexible load-3 is having more consumption during April 26 corresponding to the flexible devices and more flex-offers are available during the same period.

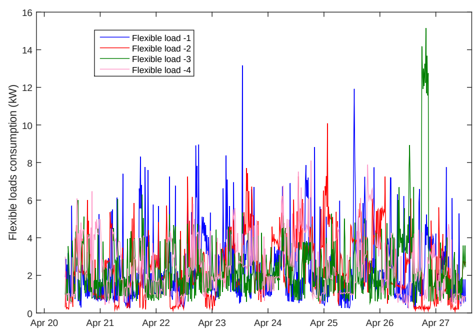

Fig. 3. Flexible devices consumption

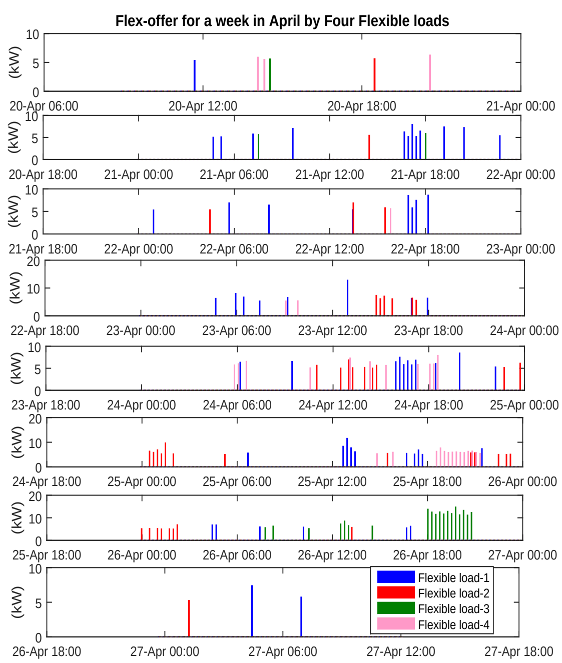

Fig. 4. Willingness of the flexible loads for shifting their demand

A. Summer Case

This section shows the study results for a summer case. Figs. 5 & 6 shows the production profiles of the solar and wind installations at the domestic loads, according to the Table II. The voltage profile of 5 load points selected from the various locations in the distribution network with the given penetration of solar, wind and flexible loads is shown in Fig. 7. It can be observed, that the voltages fell below operational limits beyond +/- 5 % at certain loads.

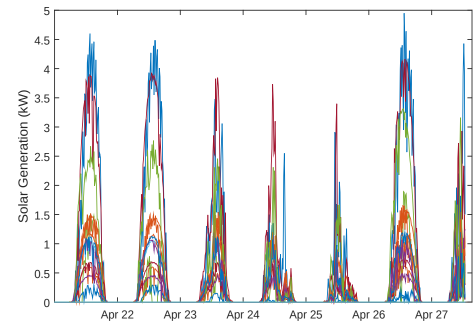

Fig. 5. Summer case: Solar production at domestic loads

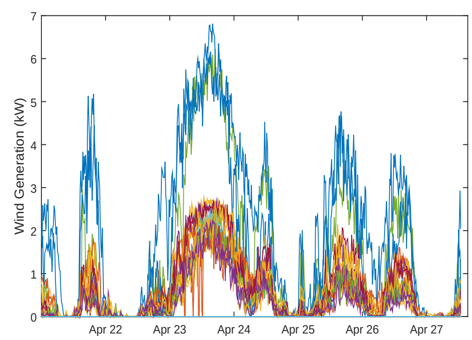

Fig. 6. Summer case: Wind production at domestic loads

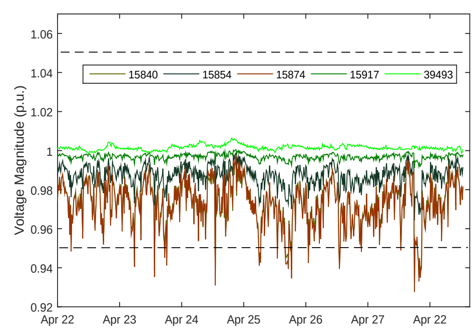

Fig. 7. Summer case: Voltage profile before flex-offers

The output obtained by the formulation given in (1) for summer case is shown in Fig. 8. Fig. 8 shows the aggregated flexible demand that need to be shifted in ‘blue color’ and the shifted flexible demand in ‘red color’. In order to plot both before and after execution of flex-offers in the same figure negative sign is assigned. Else the ‘red color’ data points gives the information about the shifted flexible load for bringing back the system to safe operational limits. The shifting time is chosen to be the next time period which can accommodate the demand. It can be applied for intra-hour and hourly electricity market. Fig. 9 shows the voltage profile after the execution of the flex offers, the system operation limits are restored. It is to be observed that in Figs. 7 & 9, the colors used are same as that of the heat-map given in the Fig. 2. In Fig. 8, on April 23rd evening, an aggregated flexible load of 60 kW is shifted within next half-an hour as the distribution network could accommodate that amount of power within next half-an hour. The resultant total demand and transformer loading of the distribution network for the summer case is shown in 10.

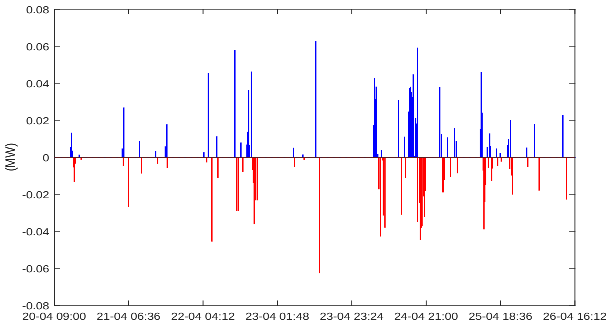

Fig. 8. Summer case: Aggregated flex-offers

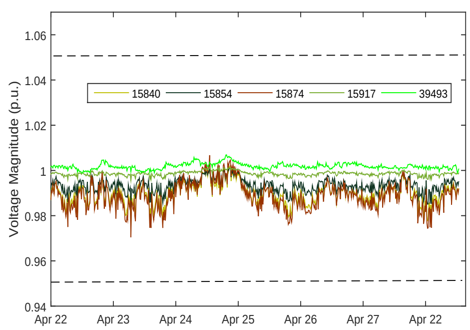

Fig. 9. Summer case: Voltage profile after flex-offers

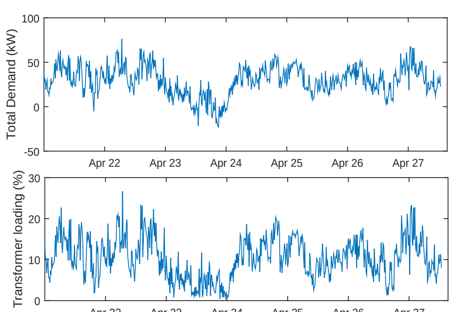

Fig. 10. Summer case: Total demand and transformer loading

B. Winter Case

For the winter case, a week in December month is chosen. The solar and wind production profiles of the domestic loads is shown in the Figs. 11 & 12. It can observed from Fig. 11, the solar production in winter is very low which validates the real time data considered. the The willingness of the flexible loads to shift their demand with respect to time is considered as shown in Fig. 3 which is used for the summer case too. The voltage profile at the selected nodes that are sparsely distributed in the considered low voltage grid is shown in Fig. 13 and it can be observed that voltages are exceeding the limits.

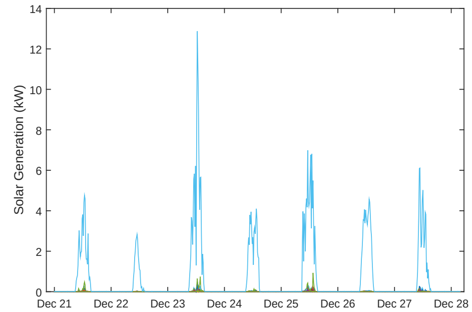

Fig. 11. Winter case: Solar production at domestic loads

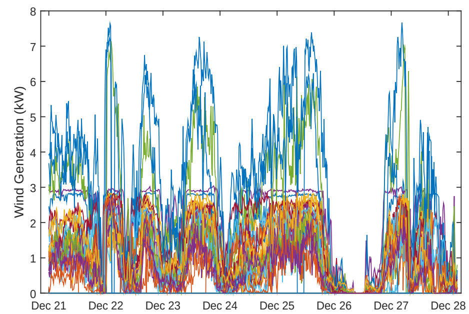

Fig. 12. Winter case: Wind production at domestic loads

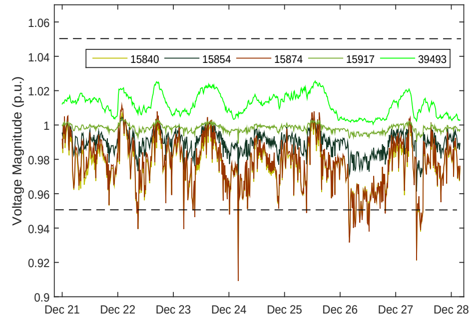

Fig. 13. Winter case: Voltage profile before flex-offers

Fig. 14 shows the flex-offers that are to be shifted in ‘blue color’ and flex-offers that are shifted in ‘red color’. It can be observed there are some days in December where within a day there are more flex-offers that are to be executed for the safe operation of the distribution network. It can also be observed in Dec. 24, a flexible demand of 0.13 MW needs to be shifted and is distributed within the next hour because of the network limitations. The voltage profile at selected nodes in the distribution network is shown in Fig. 15, from which it can be observed the network is restored to considered operation limits. Finally, the resultant transformer loading and the total demand of the distribution network is shown in Fig. 16. In Figs. 13 & 15, the colors used are same as that of the heat-map given in the Fig. 2.

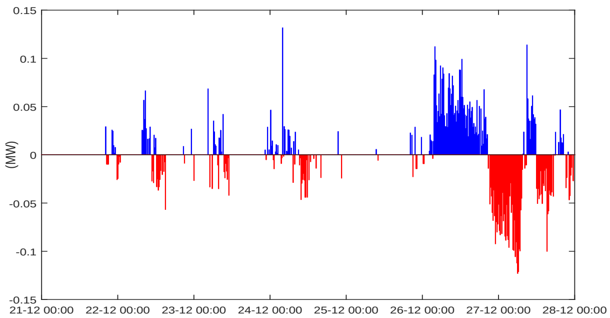

Fig. 14. Winter case: Aggregated flex-offers

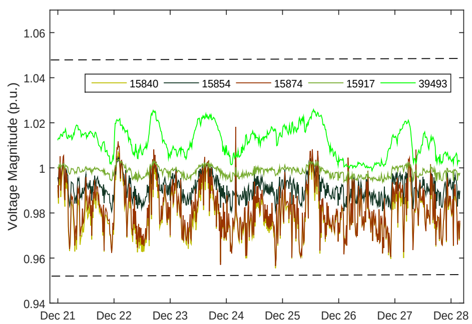

Fig. 15. Winter case: Voltage profile after flex-offers

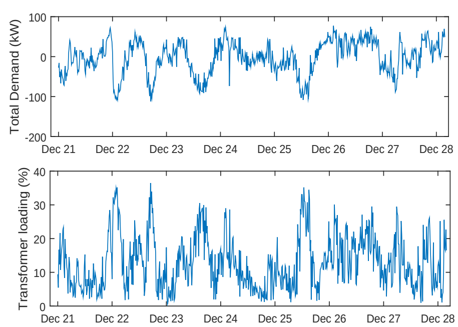

Fig. 16. Winter case: Total demand and transformer loading

IV. Discussions

From Figs. 8 & 14, the following observations are drawn,

- Aggregated power measurement that is obtained from the proposed algorithm are shifted within hour or to next day.
- For winter case, it can seen from Fig. 14, on Dec 26 there is large flexible demand available which could not accommodated within next hour but to the next day.
- This period can become a good business case of interest for the DSO/aggregators to bid in the flexibility market.
- The present study did not consider any market transactions involving other market players, rescheduling the flex-offers with respect to the electricity price, which is an interesting topic to be investigated as a part of future work.

V. Conclusions

In this paper, a DR methodology is proposed for the distribution system which contains flexible devices such EVs and heating loads, subjected to the constraints on the voltage limits and network congestions. The proposed algorithm finds the aggregated flex-offers at given point of time which can be used for responding to either technical issues or electricity price. The former is used in this work. The results clearly shows the restoration of system operation limits with the generated optimal aggregated flex-offers for the flexible loads. The customers that offered the flexibility to the DSO/aggregator will get their benefits reflected according to their flexibility consumption. The DSO benefits from the proposed flex-offers by preventing any network congestions or voltage problems. Furthermore, the information about the flexibility encourages DSO to actively participate in either day-ahead or intra-hour market resulting in engrossing better benefits both technically and economically.

Acknowledgment

The research work presented in this paper was conducted within the context of the TotalFlex and Arrowhead projects.

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