Preparation of Demand response management: Case study

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Abstract This article describes the implementation of an incentive-based demand response program. The DR program offers two types of services. The first one corresponds to the disconnection of manageable power for every hour of the day. The second one is a demand peak cutback operation. The parameters, variables, target function and restrictions of the proposed optimization problem are described for the DR program. Finally, the tests carried out for each service with the participation of a five-user group are shown along with their impact on the energy demand curve.

Index Terms— demand response, demand aggregator, manageable power, objective function, peak cutback, power disconnection dispatch.

I. Introduction

The demand response (DR) is defined as the set of strategies that influence the energy consumption of different participants in the energy market through incentives or price reduction [1]. In price-based DR programs, users can reduce their consumption as a response to the price dynamics imposed by the network operator or by the energy market. These programs are mainly cemented in the Time of Use (ToU) [2] [3] and the price dynamics in real time [4][5][6]. Some comparative studies regarding the plans of ToU-based pricing and in real time use a testing system that relates the cost of electricity generation and the establishment of fixed fees [7]. The price-based DR programs can be framed within the integral management of the buildings aiming at a higher efficiency of energetic resources [8][9][10]. For the application of price-based DR, the network's infrastructure must be optimized by controlling small loads of home appliances when an increase in prices is detected. This detection is supported by the communications system that are a property of the distribution energy company [11][12]. Incentive-based DR programs lead users to commit individually or collectively on reducing their consumption during a certain time period in terms of the technical or economic requirements of the network operator. Users enter bidding processes to reduce the demand as seen in [13]. The reduction of demand through the management of the payload corresponds to the amount of kW that a user can disconnect in certain hours of the day [14][15]. The Government must promote the initial stages of these programs [16] as well as the incentives and their continuous restructuration according to the types of users, their power levels and participation times [17] which will be reflected in changes of the demand curve [18].

On occasions, the disconnection of the charges is performed by an aggregator supported on optimization algorithms to reduce load peaks [19]. An aggregator is an independent agent that manages a certain number of users as a single unit so it is possible to negotiate the purchase of electricity and basically carry out effective DR strategies from the electric system operator's point of view. The aggregator interacts with a lower level which is the distributed demand in this case by executing several DR programs and coordinating the modification of the consumption of different end users through communication, control and monitoring systems. Additionally, there must be an interaction at higher level such a system operator to offer aggregated flexible products and participate in the electric market [20][21].

This article presents the mathematical formulation for the operation of an incentive-based DR program considering industrial clients. In section I, the DR concept is revised. In section II, the optimization problem to be solved is described within the manageable power dispatch framework of every user included in the DR strategy. Section III states a case study with two demand response programming scenarios: total reduction of the demand curve and peak elimination. Section IV shows the analysis and discussion of the results. Finally, a set of conclusions are exposed.

II. OPTIMIZATION PROBLEM FOR THE INCENTIVE-BASED DEMAND RESPONSE PROGRAM

To present the optimization problem, the parameters, variables and restrictions are initially analyzed.

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Parameters:

P_i is the maximum manageable power value that each user agrees to reduce with the DR aggregator during every hour of the day (equation 1).

$$P_i = [P_1, P_2, P_3, \dots, P_N] \tag{1}$$

where $P_1, P_2, P_3, \dots, P_N$ correspond to the amounts of manageable power that each user i can contribute in the reduction of consumption during a specific day.

To calculate the manageable power of every user (equation 2)

$$P_i = \frac{DDVVP_{im}}{720} \tag{2}$$

$DDVVP_{i,m}$ is the verified voluntary disconnected demand of user *i*, in month *m* and it is considered to calculate the disconnected definitive demand. The calculation of $DDVVP_{i,m}$ is achieved with equation 3.

$$DDVVP_{i,m} = (CME_{i,m-12} \times (1+e)) - Me_{i,m} \tag{3}$$

Where $CME_{i,m-12}$ is the monthly consumption of user *i* in the month *m* – 12 expressed in kWh. This will be the consumption of the month *m* in the previous year.
e is the average error which is equal to 0.05
$Me_{i,m}$ is the amount of energy measured in the commercial frontier of user *i* in the month *m*. The value of 720 represents to the total number of hours per month[22].

CF_i is the fixed cost of managing user *i* for each day given in USD.
$CV_{i,h}$ is the variable cost that the offered service will have on user *i* for every hour of the day given in USD/kW.
D_h is the power demand in kW for every hour. It is that the power of the network operator requests that the DR aggregator reduces in every hour of the day in kWh. This demand can be given for every hour or only during specific moments such as peak hours.

The request of energy reduction is structured through a power reduction vector in kW for each hour of the next day. As an example, the vector form D_h called hourly reduction demand vector is illustrated in equation 4.

$$D_h = [D_1, D_2, D_3, \dots, D_{24}]^T \tag{4}$$

where D_1, D_2, …, D_{24} are the power reduction demands for each hour of the day.

$KMAX_i$ is the maximum number of times in the day that a user can participate in handling a power reduction demand. This parameter is settled between the user and the DR aggregator.

Variables:

Z_{ih} Binary variable that can take the following values:

$$Z_{ih} = \begin{cases} 0, \text{ if the resource of user } i \text{ is not used in hour } h \\ 1, \text{ if the resource of user } i \text{ is used in hour } h \end{cases}$$

$i = 1,2,3, \dots, N$ is the number of users

$h = 1,2,3, \dots, 24$ are the hours of the day

To satisfy the request of the power reduction for every hour, the aggregator can decide that a user or a group of users "can participate" or "not participate" at any hour. This decision will be expressed with a Z_{ih} indicator that take values of 0 when a certain user is not included in the request in the hour *h* and values of 1 when the user participates in the request.

P_{ih} Variable that shows the power with user *i* participating in hour *h* and it is expressed in kW.

Target function

The target function is shown in equation 5

$$min \sum_h^{24} \sum_i^N [CF_i * Z_{ih} + CV_{ih} * P_{ih}] \tag{5}$$

$$\sum_{i=1}^N P_{ih} \geq D_h \tag{6}$$

where

$h = 1,2,3, \dots, 24$ represent the hours of the day

$$0 \leq P_{ih} \leq P_i * Z_{ih} \tag{7}$$

$$\sum_{h=1}^{24} Z_{ih} \leq KMAX_i \tag{8}$$

Restrictions:

The first restriction is related to the coverage of the demand made each hour (equation 6). The second restriction refers to the maximum unplugged power limits for each user in the case that is requested to participate in the DR program (equation 7). The third restriction involves the maximum number of times that a user can participate in DR program during the day (equation 8). Every user is conditioned to only participate a limited number of times per day. The distribution network operator performs a request to the DR aggregator so he can coordinate the reduction of the energy consumption of certain users for the next day when the request is received. This transaction scheme is called day ahead [23] [24]. The DR aggregator satisfies the reduction demands with the manageable power resource of a limited group of users assembled through the aggregator [14].

To evaluate the behavior of the program of the response of the demand to the orders of the network operator an algorithm was developed as following:

1. Enter the characteristic parameters of the users who participate in the DR program.
2. The power disconnection request is received by the network operator.
3. Those users whose number of participations for a certain time of the day do not exceed the KMAXi.
4. The verification of the resources available per user is made for each hour requested. At this point it is observed with what manageable power is counted by the users for a particular hour.
5. Those users that have sufficient manageable power and at the minimum cost to meet the required demand are selected.
6. The offer is sent to the operator of the network and the respective payments for the service are established

III. CASE STUDY

With the purpose of performing an analysis of the optimization problem based on the DR program, a case study was defined by taking a typical demand curve for industrial users. As a test scenario, a 34-node IEEE network illustrated in Figure 1 was used.

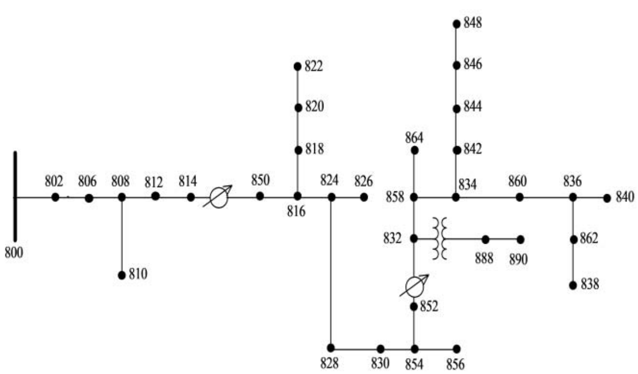

Figure 1. IEEE-34 nodes used as a test network.

Table 1 shows the characteristic parameters of the loads that make up the test network.

The Sizing of the loads of IEEE model is shown in the Table 2. The users that participate in the demand response program during a day are underlined and bold. A total of 10 users who participated in the DR program were defined, to select these users it was started from the largest power capacity. (users in DR program are shown underlined).

To solve the optimization problem, the initial parameters and internal restrictions of the DR program are used. The optimization problem was analyzed as a mixed-integer type problem since it contains continuous variables such as unpluggable powers P_{ih} and integer variables such as the participation index of the users Z_{ih} in each hour of the DR program [25]. To assess the results, 10 industrial users were assigned parameters referring to the costs and unpluggable powers that are shown in Table 3.

Table 1. Power parameters for loads in the IEEE-34 network

LOAD	POWER		LOAD	POWER	
	ACTIVE (kW)	REACTIVE (kVAr)		ACTIVE (kW)	REACTIVE (kVAr)
816	5	2,5	824	24,5	12
842	5	2,5	806	27,5	14,5
864	5	2,5	802	27,5	14,5
856	5	2,5	846	34	17
854	5	2,5	**840**	**47**	**31**
828	5,5	2,5	**830**	**48,5**	**21,5**
832	7,5	3,5	**836**	**61**	**31,5**
810	8	4	**822**	**67,5**	**35**
808	8	4	**848**	**71,5**	**53,5**
862	14	7	**820**	**84,5**	**43,5**
838	14	7	**834**	**89**	**45**
818	17	8,5	**860**	**174**	**106**
826	20	10	**844**	**432**	**329**
858	24,5	12,5	**890**	**450**	**225**

Table 2. Fixed costs for the participation and unpluggable power for the 10 users included in the test.

User	840	830	836	822	848	820	834	860	844	890
CF_i, USD	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
$CV_{i,h}$, USD	0.07	0.08	0.10	0.10	0.06	0.06	0.05	0.06	0.07	0.08
$KMAX_i$	3	4	3	4	4	3	3	4	4	4
$P_{i,h}$, kW	10	20	20	60	40	90	40	20	60	40

Different tests were carried out for two scenarios with unplugging demand vectors. The solution of optimization problem in each case was developed with software GAMS.
The first power-unplugging scenario occurs when the network operator requires a power reduction for every hour of the day. The power unplugging demands for this scenario are shown in Table 3. The reduction of the demand curve during the service dispatch is illustrated in Figure 2. In the second scenario, the network operator only requires reductions on the following timeslots corresponding to peak demands of the next day. The values of the power-unplugging vector for the peak slots are shown in Table 4. Figure 2 shows the behavior of the demand curve once the peak elimination program is applied.

Table 4. Power-unplugging demand vector for every hour of the day

	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}	h_{11}	h_{12}
D_h, kW	20	20	20	10	10	30	30	20	20	40	42	20
	h_{13}	h_{14}	h_{15}	h_{16}	h_{17}	h_{18}	h_{19}	h_{20}	h_{21}	h_{22}	h_{23}	h_{24}
D_h, kW	30	20	30	20	10	10	30	30	30	20	20	20

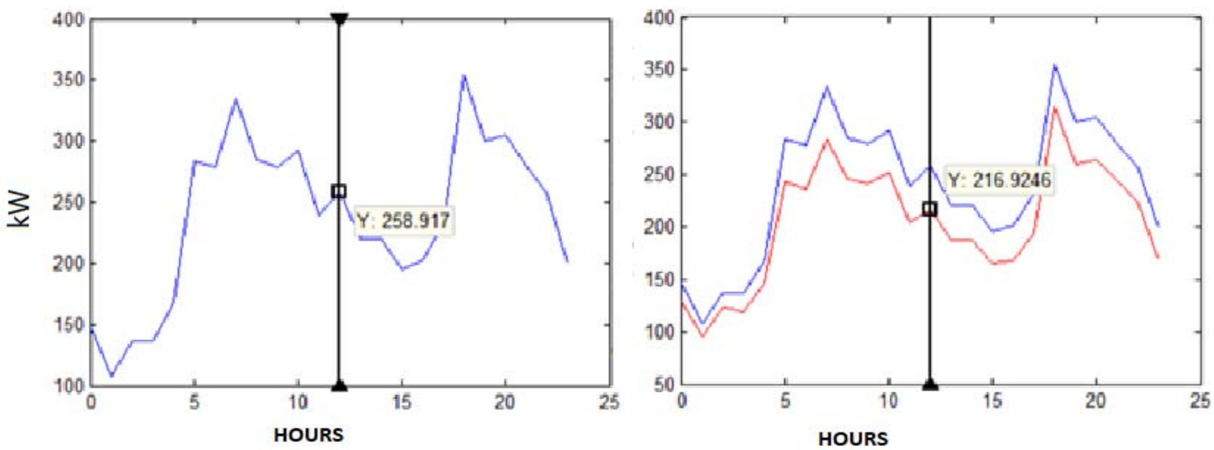

Figure 2. Hourly behavior of the demand curve after applying the disconnection dispatch program
Left – Initial Curve
Right – Curve with applied service

The behavior of the users to respond to the DR program by disconnecting their manageable loads during the 24 hours can be seen in figure 3.

Participation in the first hours of the day focuses on users who have the capacity to respond to the requested demand and offer the best cost ratio, which corresponds to users 7 and 5.

However, the restriction on the number of shares makes it possible for all other users to participate in the program even if their costs for the disconnection service offered are high such as users 3 and 4). The total cost of the service of disconnection of the manageable demand offered by the users is 45,6 USD.

For the peak trimming scenario there is a disconnection demand vector only for some hours of the day. Table 5 shows the details of the disconnection request made by the network operator for some peak consumption hours in the day. Figure 4 shows how the usual consumption demand curve decreases during peak hours. The way users respond to disconnection requests made focuses once again on meeting the demand required, taking into account the least cost and meeting the restrictions on the number of users' participation (figure 5).

The cost of the disconnection service is 81,32 USD because the demand for power is greater, it is required to cover the orders of disconnection demanded and the lowest possible cost. With the inclusion of the restriction on the number of participations, users with lower costs are dispatched, giving way to users with higher costs but who guarantee compliance with the disconnection service.

IV. Results analysis

For both scenarios, it is evident that the incentive-based DR program reduces the demand curve. User participation is first given in terms of the availability of unpluggable power resources for every hour and then in terms of the minimum cost offered by users. In non-restricted scenarios, the number of participants could lead to lower costs than the ones stated but it could affect equalitarian participation for all grouped users.

The total cost of the disconnection services applied to every hour of the day was 144.570 USD while the total cost of the consumption reduction service for only peak hours was 145.07 USD. It is evident the flattening of the demand curve in the peak elimination service even if it requires the participation of the majority of manageable resources from the users.

The similarity in costs for the two types of demand reduction services for each hour and the peak elimination can be explained by the reduction of the demand curve in kWh which is very similar for both.

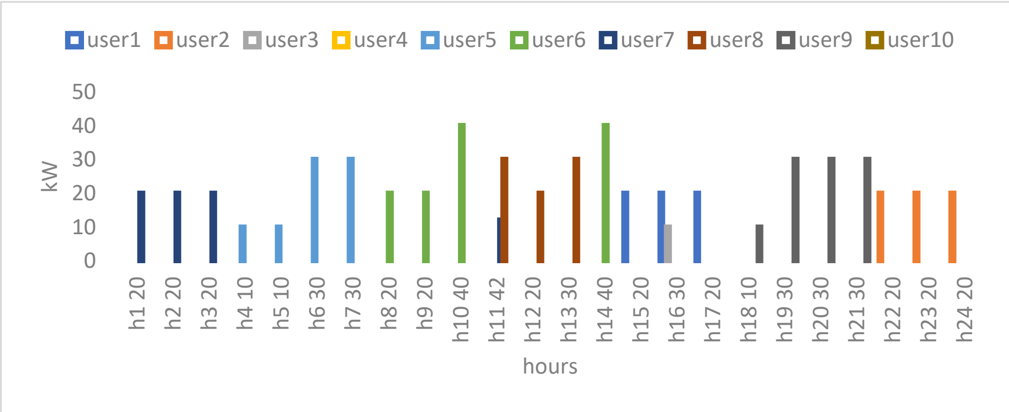

Figure 3. Hourly behavior of the users

Table 5. Power-unplugging demand vector only for peak hours

	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}	h_{11}	h_{12}
D_h, kW	0	0	0	0	80	100	110	100	90	10	48	10
	h_{13}	h_{14}	h_{15}	h_{16}	h_{17}	h_{18}	h_{19}	h_{20}	h_{21}	h_{22}	h_{23}	h_{24}
D_h, kW	0	0	0	0	0	10	100	80	90	100	78	0

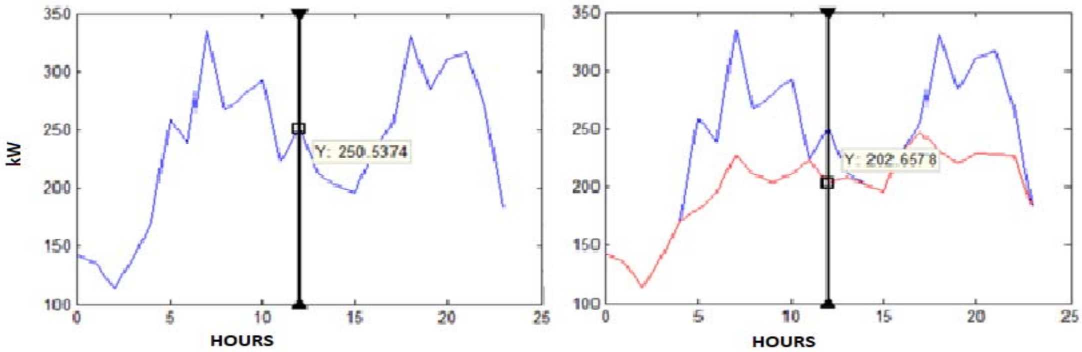

Figure 4. Hourly behavior of the demand curve after applying the demand peak cutback program
Left – Initial Curve
Right – Curve with applied service

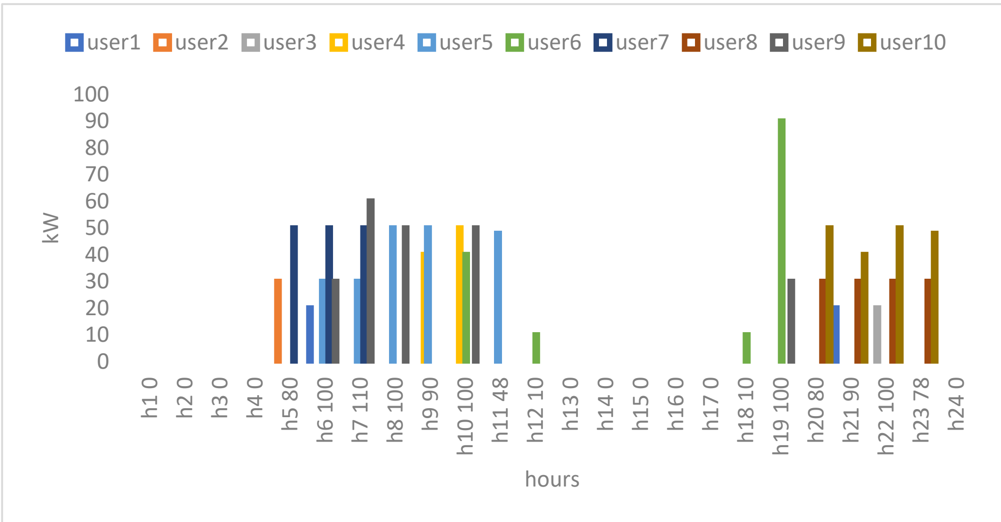

Figure 5. Hourly behavior of the users in peak reduce

V. CONCLUSIONS

The manageable power-unplugging dispatch strategy supported by DR is very flexible and can be accommodated to scenarios with diverse management objectives ranging from the economic to the technical point of view, specifically related to the reliability of the energy provider.

The peak elimination service based on a DR program allows the network operator to reduce the costs in the energy purchase market to the generators. The economic benefit translates into the users that have the opportunity to receive dividends from the power that they willingly decided to unplug and that remains below the consumption baseline that was previously established with the operator.

It is noteworthy to mention that the inclusion of the maximum number of participations per user offers the possibility to all users to participate in DR programs and not only those that offer a lower price.

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