Definition of Distinct Consumer Modelling Approaches for the Participation in Demand Response Programs Considering Distributed Generation

Fábio Pereira, Pedro Faria, Zita Vale
GECAD - Knowledge Engineering and Decision Support Research Center
IPP - Polytechnic Institute of Porto
Porto. Portugal
faper@isep.ipp.pt. pnfar@isep.ipp.pt. zav@isep.ipp.pt

***Abstract*—The increasing use of Distributed Generation (DG) resources, as well as the introduction of Demand Response (DR) resources has motivated significant changes in the context of competitive electricity markets and smart grids. The methodology proposed in this paper aims to allow scheduling the DG and DR programs resources, considering the implementation of distinct approaches for DR programs remuneration, such as, Steps, Quadratic, Constant, Linear and Elastic. This methodology can be used by a Virtual Power Player (VPP) that aggregates and manages small size consumption resources, enabling them to participate in DR programs. Distinct levels of energy/price from external suppliers are considered in the case study that accommodates 4 external suppliers, 66 DG units, and 218 consumers, classified into 6 types of consumers. For each context the aggregator is able to discuss on the adequate remuneration approach.**

***Index Terms*—Consumers modelling, demand response, distributed generation, remuneration, virtual power player.**

NOMENCLATURE

Variables

P	Power of each resource [kW]
$C_{E}^{Increase}$	Elasticity Cost increase [m.u./kW]

Parameters

α_{DR}	Maximum allowed DR contribution [%]
C	Cost of each resource [m.u./kW]
NC	Total number of consumers *c*
NG	Total number of distributed generation *g*
NSp	Total number of suppliers *sp*
PEC	Price Elasticity of the Consumption
P_{Load}	Power scheduled for the consumption [kW]

Indexes

c	Consumer index
g	Distributed generation index
sp	External supplier index

Subscript

Const; E; L; Q; S	DR Constant, Elastic, Linear, Quadratic and Steps programs
DG	Distributed Generation
Increase	Maximum resource *E* program
Initial	Initial resource *E* program
NSP	Non-supplied Power
Supplier	External Supplier

Superscript

a; b; c	Quadratic, linear and constant coefficient
i; ii; iii	Each elementary step

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I. INTRODUCTION

The presence of Distributed Generation (DG) and Demand Response (DR) programs allows to change the paradigm of electric power systems, providing benefits within the framework of management and operation of a power system [1]. The use of DG resources together with the implementation of DR programs allows to improve the results resulting from the smart grids and electricity markets [2].

DR programs have the particularity to allow an active role of consumers, through its consumption reduction, in the power system management. There are several benefits that are inherent in use of DR programs, being useful in critical conditions of operation of a power system [3]. Furthermore,

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the use of DR programs can bring economic benefits and can lead to the optimization of operation costs [4].

In the same way, the integration of DG resources takes into account environmental issues and allows electricity generation geographically and electrically close to the consumption locations. It can provide power directly to consumers and can also be connected to a distribution network and supply other consumers [5]. The DG and DR are distributed small-size resources, which require entities that make their in order to achieve all the advantages that these resources bring for the power system and electricity markets. Entities able to aggregate and manage several small-size resources, such as DG and DR (consumers that participating in DR programs), known as Virtual Power Plants, although lately are referred to as Virtual Power Player (VPP) [6].

With regard to consumers, VPP must find adequate models and approaches in order to incentive consumers to participate in DR programs. The literature in this field, although it can propose different remunerations approaches, usually proposes a remuneration scheme similar for all consumers, making no distinction between consumers that have different characteristics [7]. The remuneration of consumers is based in models that consider several approaches, namely, logarithmic, exponential and elasticity models [8]-[10]. As consumers have different characteristics, their interests will also be different, that is why the VPP should take into account the adequacy of models to each type of consumer, as discussed in [11].

The use of DG and DR resources has already been addressed in other works, as in [12]. According to [12], the remuneration approach is made equally for all types of consumers following a linear remuneration, i.e., this does not vary with the amount used, distancing itself from paper proposed in this work, as well as in [11]. The proposed methodology in this paper is based on the previous research presented in [11], in which the VPP is able to manage the distribution network and the respective resources, using distinct DR programs approaches, designated by Steps, Quadratic, Constant, Linear and Elastic. Furthermore, in the present paper, the proposed methodology also addresses the management of DG resources by the VPP.

This methodology includes approaches of DR programs fits in classification that belong to incentive based DR and to price based DR, and enables to model adequately the remuneration of consumers, while reducing their consumption. The VPP is able to meet several scenarios and make an optimal scheduling resources for each situation, such as, operating a network critical situations, for example, lack of energy supplied or lines and others elements outages. The scheduling of resources made by the VPP always considers minimization of operation costs.

This paper is organized as follows: after this introductory section, Section II presents the proposed methodology and explains the mathematical formulation of the optimization problem. Section IV shows the case study, in Section IV illustrates the obtained results and Section VI the conclusions.

II. PROPOSED DR AND DG METHODOLOGY

In this section is presented the proposed methodology in subsection II-A, and subsection II-B is identified in detail the formulation of the optimization problem.

A. *Proposed Methodology*

The methodology proposed aims the minimization of operation costs through an optimal resources scheduling, considering the use of DG and DR programs resources. Moreover, this methodology can be used by the VPP, in order to aggregate and manage small size consumers by implementing of distinct approaches of DR programs remuneration. The variation of price characteristics and energy provided by external suppliers is considered, allowing that DG resources and implementation of DR programs ensures the demand. At the same time, the issues of economic scheduling are taken into account, for each scenario.

In Fig.1 is illustrated the proposed methodology, where VPP should consider multiple information initial data, including data on the characteristics of generation (DG e external suppliers) resources, as well as the characteristics of the consumers targeted. The five types of models that can be considered by the VPP to model consumers are referred to as Steps, Quadratic, Constant, Linear and Elastic.

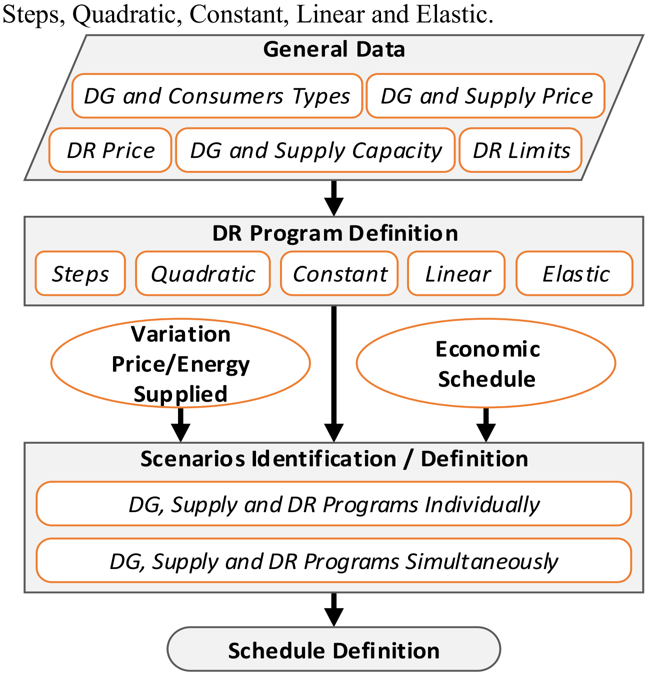

Figure 1 – Diagram of the proposed methodology.

Several scenarios are considered in view of the possibility of critical situations of operation related to the variation in price and energy supplied from the external suppliers. VPP is able to discuss the DR programs and DG resources taking into account the best economic scheduling in each context. For each scenario the DR programs may be implemented individually or simultaneously. When the DR programs are applied simultaneously, these are associated with different consumers, in order to enable each consumer can have only two DR programs available approaches. On the other hand, when the DR programs are associated individually, all consumers can be associated with each DR program. The proposed methodology contributes and is innovative in the following aspects:

- Remuneration of consumers through of modelling of five distinct types of DR programs (Steps, Quadratic, Constant, Linear and Elastic);
- Definition of the most advantageous modelling approach combined with DG resources in each context of variation price/energy supplied and economically advantageous;
- Implementation of optimization constraints for the VPP to determine optimal energy resources scheduling, and characterize the influence to be associated to each DR program and to a set of DR programs in which a certain consumer is participating.

B. *Mathematical Formulation*

For this problem, the resources schedule optimization is obtained with use of TOMLAB [13]. The objective function is given by (1), where minimization of Operation Costs (*OC*) comprises the Costs (*C*) and energy (*P*) respective of each generation and consumption resource.

$$Minimize\ OC = \left[\begin{array}{l} \sum_{sp=1}^{NSp} \left(P_{Supplier(sp)} \times C_{Supplier(sp)} \right) + \sum_{g=1}^{NG} \left(P_{DG(g)} \times C_{DG(g)} \right) \\ + \sum_{c=1}^{NC} \left[\begin{array}{l} \left(P^{i}_{S(c)} \times C^{i}_{S(c)} + P^{ii}_{S(c)} \times C^{ii}_{S(c)} + P^{iii}_{S(c)} \times C^{iii}_{S(c)} \right) \\ + \left(P^{2}_{Q(c)} \times C^{a}_{Q(c)} + P_{Q(c)} \times C^{b}_{Q(c)} \right) \\ + \left(P_{Const(c)} \times C_{Const(c)} \right) \\ + \left(P_{L(c)} \times C^{b}_{L(c)} + C^{c}_{L(c)} \right) \\ + \left[\left(P^{Initial}_{E(c)} - P_{E(c)} \right) \times \left(C^{Initial}_{E(c)} + C^{Increase}_{E(c)} \right) \right] \\ + \left(P_{NSP(c)} \times C_{NSP(c)} \right) \end{array} \right] \end{array} \right] \quad (1)$$

From (1) it can be seen the distinct characteristics of each DR program approach, allowing to VPP the modelling of consumers in different ways. The first DR program approach presented in (1) corresponds the Steps program, which it is characterized by providing three distinct prices to three levels (*i, ii, iii*) of energy power that consumer can reduce. The price of the first level will be lower than of the second, and the second level will have a lower price than of the third, corresponding to an evolution of remuneration similar to a ladder. DR Quadratic program has the particularity that the price received by the consumer, with a quadratic trend. This program include quadratic (*a*) and linear (*b*) coefficient. Two similar approaches are addressed by the DR Constant and Linear programs. The Constant program always involves the same price to remunerate the participation of consumers, i.e., it is independent of the amount of reduced energy. As for the linear program apart from consumer receive through the amount of energy, at a constant price, also receives a fixed cost (*c*) that results from the compromise between the consumer and aggregator. DR Elastic program depends, essentially, on the amount used and the price for such use. In (3) is shown the constraint that affects this program. Several constraints are considered by the VPP for the optimal scheduling of resources, including basic and essential condition for ensures the balance of the electric power system, given in (2).

$$\begin{array}{l} \sum_{c=1}^{NC} P_{Load} = \sum_{sp=1}^{NSp} P_{Supplier(sp)} + \sum_{g=1}^{NG} P_{DG(g)} \\ + \sum_{c=1}^{NC} \left[\begin{array}{l} P^{i}_{S(c)} + P^{ii}_{S(c)} + P^{iii}_{S(c)} + P_{Const(c)} \\ + P_{Q(c)} + P_{L(c)} + P_{E(c)} + P_{NSP(c)} \end{array} \right] \end{array} \quad (2)$$

In (3), it is defined the Price Elasticity of the Consumers (*PEC*). This condition is affected by the initial amount of use of the service, designed P_E (*Initial*), and the price, C_E (*Initial*), relating to this service. The variation of amount of use and price is represented by P_E and C_E (*Increase*), respectively.

$$PEC_{(c)} = \frac{P_{E(c)} \times C^{Initial}_{E(c)}}{P^{Initial}_{E(c)} \times C^{Increase}_{E(c)}} \quad \forall c \in \{1,...,C\} \quad (3)$$

The constraints mentioned in (4) and (5) only apply when the DR programs are implemented in simultaneously, allowing the VPP manage the contribution of DR programs in scheduling resources. Equation (4) shows the condition that allows the VPP manage the use percentage of each DR programs, which is given by the parameter α_{DR}. Consumption reduction of each DR program is limited, being defined that each DR program can only be responsible by a maximum considered relative the total consumption reduced.

$$\frac{\sum_{c=1}^{NC} P_{Const(c)}}{\sum_{c=1}^{NC} \left[\begin{array}{l} P^{i}_{S(c)} + P^{ii}_{S(c)} + P^{iii}_{S(c)} + P_{Q(c)} \\ + P_{Const(c)} + P_{L(c)} + P_{E(c)} \end{array} \right]} \le \alpha_{DR} \quad (4)$$

The participation of each consumer in DR programs is limited by (5). This way, VPP is only able to use a certain amount, which is always less than the initial consumption of each consumer.

$$\begin{bmatrix} P^{i}_{S(c)} + P^{ii}_{S(c)} + P^{iii}_{S(c)} \\ +P_{Q(c)} + P_{Const(c)} \\ +P_{L(c)} + P_{E(c)} \end{bmatrix} \leq P^{Max}_{Total(c)} \quad \forall c \in \{1,...,C\} \qquad (5)$$

The full problem formulation also include the maximum and minimum bounds of each resource (DG, external suppliers and DR programs) and maximum and minimum limits of each consumer can reduce/consume. Maximum price and power variations in the DR Elastic program also is considered.

III. CASE STUDY

The proposed methodology has been applied to a case study where the VPP manages 218 consumers, 66 DG units and 4 external suppliers. The consumers are classified in six types – Domestic (DM); Small Commerce (SC); Medium Commerce (MC); Large Commerce (LC); Medium Commerce (MC) and Large Industrial (LI).

The total consumption is 5827 kW. In the case study is considered other data on consumers, number and amount of consumption for each set consumer type. These values are, respectively: DM – "120", "1481.45"; SC – "46", "961.25"; MC – "23", "743.90"; LC – "13", "423.15"; MI – "7", "423.15"; LI – "9", "1243.65". Table 1 are identified the prices of each DR programs approach for each consumer, based on [14]-[15].

For the DR Linear program, the constant coefficient (*c*) corresponds to 1% of the price applied by the DR Constant program, for each consumer, while the linear coefficient (*b*) results from the difference between the two values mentioned above. As regards the DR Quadratic program, the quadratic coefficient (*a*) corresponds to 0.01% of the price the DR Constant program, and the linear coefficient (*b*) has the same value of prices charged by the DR Constant program. DR Steps program has three distinct prices, for each level of consumption reduction by consumer type. For DR Elastic program is presented initial price – C_E (*Initial*), and parameter of the Price Elasticity of the Consumer (*PEC*) is presented too (indicated in yellow), and it is non-dimensional parameter.

In Table II is identified the characteristics of distinct DG and external suppliers resources, based on [14].

TABLE II. GENERATORS CHARACTERISTICS AND PRICES.

Type of generator	Number of Units	Total capacity (*kW*)	Min price (*m.u./kWh*)	Max price (*m.u./kWh*)
Photovoltaic	32	502.2	0.145	0.254
CHP	15	1240	0.0001062	0.065
Fuel Cell	8	235	0.095	0.11
Small Hydro	2	70	0.042	0.049
Wind	5	245	0.055	0.08
Biomass	3	350	0.06	0.65
WtE	1	10	-	0.056
Supplier 1	1	1200	-	0.23
Supplier 2	1	800	-	0.24
Supplier 3	1	900	-	0.25
Supplier 4	1	1800	-	0.26
Total	70	7352.2	-	-

CHP – Combined Heat Power
WtE – Waste-to-Energy

The case study aims to allow the VPP to consider the various approaches of DR programs, to meet several scenarios. For developed scenarios are considered changes in price and energy from external suppliers. To address these scenarios, the VPP can implement of DR programs, which can be implemented simultaneously or individually and should always take into account the DG resources. As mentioned in subsection II-A, when the DR programs are implemented simultaneously, these are associated with different consumers, to each consumer type be able to associate with two distinct approaches. Therefore, DM and SC consumers can be associated with the DR Constant and Linear programs, the MC are related to DR Linear and Steps programs, the LC can participate in DR Quadratic and Steps programs, and finally, the MI and LI can be combined with DR Quadratic and Elastic programs. In this case study is stipulated limit of participation of DR programs, considering the constraints mentioned in subsection II-B. Each consumer cannot reduce more than 40% of their initial consumption and individually each DR program reduces up to 25% of the initial consumption, except for the DR Steps program that is 30%, since the step *i* is 5%, the step *ii* is 10%, and step *iii* is 15%. When the DR programs are implemented simultaneously, each program can reduce up to 40% compared with the total consumption reduced by all DR programs. DR Elastic program must also follow a reduced consumption minimum of 5% of total consumption reduced by all DR programs.

TABLE I. PRICES BY CONSUMER AND DR PROGRAMS TYPES.

Prices (*m.u./kWh*)	Constant	Linear		Quadratic		Steps			Elastic	
		b	*c*	*a*	*b*	*i*	*ii*	*iii*	*Initial Price*	*PEC*
DM	0.20	0.1980	0.0020	0.000020	0.20	0.16	0.20	0.24	0.18	0.27
SC	0.16	0.1584	0.0016	0.000016	0.16	0.15	0.19	0.22	0.19	0.33
MC	0.19	0.1881	0.0019	0.000019	0.19	0.18	0.20	0.26	0.20	0.37
LC	0.18	0.1782	0.0018	0.000018	0.18	0.17	0.24	0.26	0.16	0.41
MI	0.12	0.1188	0.0012	0.000012	0.12	0.18	0.22	0.26	0.14	0.53
LI	0.14	0.1386	0.0014	0.000014	0.14	0.17	0.26	0.28	0.12	0.57

IV. RESULTS

The present section presents the results obtained by the implementation of proposed methodology to each scenario constituted by 66 DG units, 4 external suppliers and 218 consumers.

A. Participation of DR Programs Individually

Results presented in this subsection regarding the scheduling of resources (DG, external suppliers and DR programs) made by the VPP, when the DR programs are implemented individually. Fig. 2 identifies the participation of each DR program approaches, in requested scheduling of VPP, for each value of the variation power provided by external suppliers.

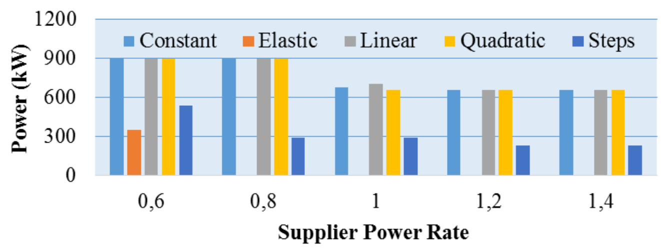

Figure 2 – Consumption reduction by DR program and supplier power rate.

Each DR program is implemented individually for each scenario, considering several levels of the amount of power delivered by suppliers (for example, level "0.6" corresponds to a reduction of 40% in the basis power; level "1" is the basis power; level "1.4" corresponds to an increase of 40% in the suppliers' power). The price of energy provided of suppliers is 30% below the basis price. As seen in Fig. 2, for this scenario, the programs scheduled by the VPP most requested for the consumption reduction are DR Constant, Linear and Quadratic programs. For the same previous scenario, the Fig. 3 shows only the participation of the DR Quadratic program for each level of power supply. It also presents the contribution of DG resources and external suppliers, in scheduling of VPP.

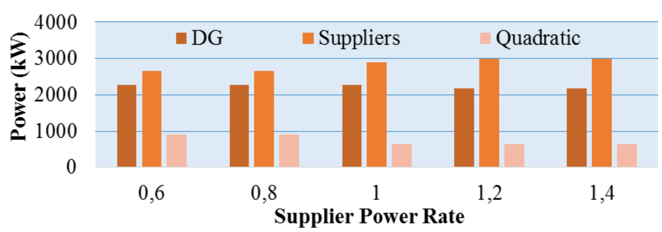

Figure 3 – Participation of DR Quadratic program, DG and suppliers.

This case presents a contribution of resources of DG uniform, while the participation of DR Quadratic program decreases with the increased availability of energy provided by the suppliers. One particular situation is presented in Fig. 4 and Fig. 5, which show the results obtained considering the basis power and the price of energy provided is 30% below the basis price, of each external supplier. In Fig.4, it is illustrated the number of consumer, by type, which participate in each DR program. All consumers are participate in scheduling of VPP, however the Domestic (DM) and Medium Commerce (MC) only is able to participate in one DR program (Steps), while the remnant consumers are able to associate to several DR programs.

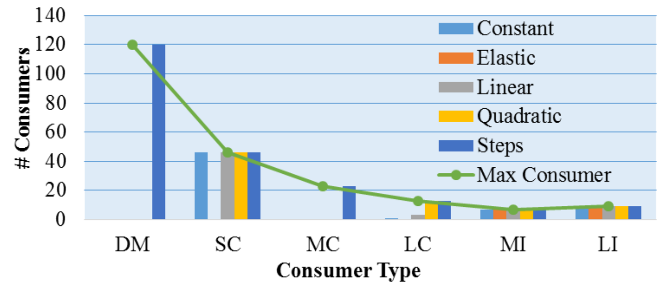

Figure 4 – Participation of consumers by DR program type.

Fig. 5 shows other important results concerning the remuneration that each DR program approach involves for each consumer, and consumption reduction made for each consumer type. VPP makes use of all consumers for scheduling resources, but the consumers of type Small Commerce (SC) and Large Industrial (LI) reduces more their consumption and, therefore, they are more remunerated. Consequently, the DR Constant Linear and Quadratic programs are the most sensitize the participation of consumers to reduce their consumption.

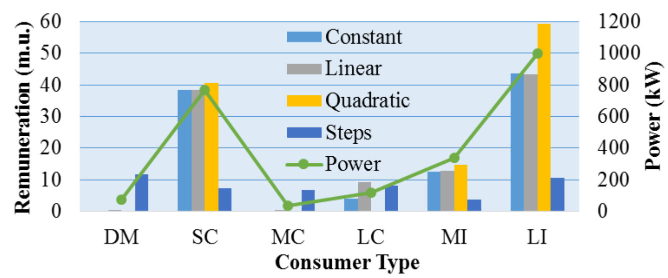

Figure 5 – Remuneration and consumption reduction by consumer type.

B. Participation of DR Programs Simultaneously

VPP can also to make use of DR programs implementing them simultaneously and carry the optimal scheduling of resources, considering the possibility of using the DG resources and external suppliers. In Fig.6 are presented three perspectives of resources scheduled by the VPP, in order to clarify the contribution of each type of resource. The scenario illustrated is based on the variation in energy prices provided from the external suppliers, maintaining their power base. For example, level "0.6" corresponds to a reduction of 40% in the basis price; level "1" is the basis price; level "1.4" corresponds to an increase of 40% in the suppliers' price. In what concerns to Fig. 6, case a) presents the results of more broadly of involvement of all three types of resource (DG, Suppliers and DR programs). On the other hand, the cases b) and c) show in detail the participation of each DG resources and each of the DR programs, respectively, for each price change in level of the energy supplied. The DR programs are implemented simultaneously that are associated the consumers that best fit, as indicated in Section III.

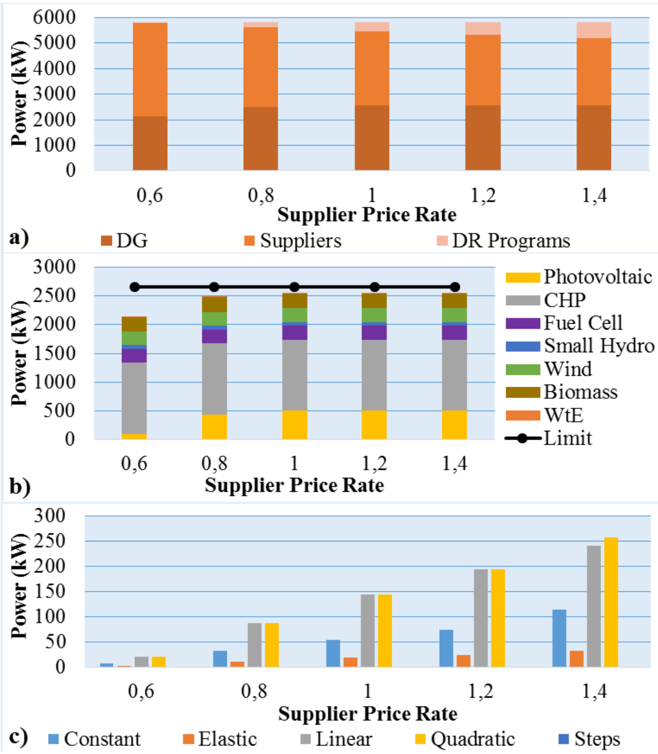

Figure 6 – Participation of each resource and supplier price rate.

As is expected, the VPP scheduled greater involvement of DG resources, as well as participation of DR programs, as the price of energy provided by suppliers is increasing, since is most economically advantageous. Within of resources of DG, the Combined Heat Power (CHP) is resource scheduled to generate the most energy, case b). Moreover, the limit of generation in total of resources DG is never reached. In relation to DR programs, case c), the programs with greater participation in scheduling by the VPP are the DR Linear and Quadratic programs.

V. Conclusions

The proposed methodology in this paper shows that in situations of power failure or in situations where the energy provided is economically disadvantageous, the use of DR programs combined with DG resources can solve the problem. The VPP can manage the electrical power system using several DR programs, distinct from each other's, allowing to develop adequate models remuneration for consumers, which can be scheduled individually or simultaneously. The DG resources can be a possibility to generate and provide energy more economic, which can be used by VPP. When the approaches of DR programs are implemented individually, the different types of consumers are more sensitive to participation in the Constant, Linear and Quadratic programs. Whereas when they are implemented at the same time, the programs with greater contribution to consumption reduction are just the Linear and Quadratic approaches. Compared with DR programs individually and simultaneously implemented, the results obtained are similar in both situations.

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