Integration of Pumping in Virtual Power Players Management Considering Demand Response

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Abstract — **The increase of distributed generation in several countries around the world brought several challenges to planning and operation of the electric network. In situations of high penetration of non-storable resources generation, mainly wind power, demand response programs and pumping may be applied, in order to encourage the increase of consumption, to guarantee a better electric network management. The present paper presents a methodology focusing on demand response programs, distributed generation and pumping, which aims to be used by a Virtual Power Player, who is able to manage the available resources optimizing its costs. The main objective is to use pump to store water to reservoirs, so the reservoir owner would have enough power to boost for energy generation. The case study includes 2223 consumers and 47 distributed generators, which was implemented using a Portuguese power system real scenario, 9th March 2014.**

Index Terms – **Demand response, distributed generation, pumping, real time pricing, smart grids, and wind curtailment.**

I. INTRODUCTION

Recent policies around the world, including in Europe, point out the necessity to integrate the growing amounts of distributed generation (DG) in the electric power systems. The renewable DG tends to avoid, increasingly, the use of fossil fuels for electricity generation, due to the rising environmental impacts caused by them. With the increase of DG, it led to the formation of demand response programs and increased the electric network complexity, which needs to guarantee more reliability and energy quality to its consumers [1]. More detailed information and practical case studies about electricity markets and demand response programs can be found in [2]-[3]. The DG, many times known as decentralized generation, is therefore considered as a good solution, once the generation tends to be in the local where the loads are, reducing the need of any high voltage transmission system, above all its implementation represents a measure of small investment. DG can bring several benefits with its development, since this type of generation is easier and quicker to develop and install, as said before, its implementation costs are also lower once it avoids long distance transmission lines [4].

The fast increase of DG units also regards several issues, mainly, wind power, which leads to wind curtailment. Wind Curtailment is applied to wind power and many times known as the generation that is not seized, avoiding wind farm operators to maximize the output power and, respectively, a higher yield, once they opt to curtail the wind available.

The leader country of wind penetration is Denmark with 27%. It is followed by Portugal and Spain, respectively with 17 and 16% [5]. The wind power installed in Europe by the end of 2014 was 133,968 MW, while in 2013 and in 2012 was, respectively, 121,474 MW and 109,581 MW, being that Germany, Spain and United Kingdom are the ones that present, along these years, the highest capacity installed [5] – [6].

In similar work to the one that is presented, is tried to develop or improve the existing bidding strategies from the Wind Power Producer, considering a low level of uncertainty, due the instability associated to the wind power generation [7].

This paper proposes a methodology to complement the problem that was initially developed in [8]. It aims to be used by a Virtual Power Player (VPP), envisioning new methods to solve different wind power generation problems. A VPP is an aggregating entity that manages the available resources based on consumption [9]. This work concerns, essentially, water storage, in reservoirs, of hydro energy using pumping and demand response. Whenever generation is higher than expected, the VPP will be able to use it in pumping or initiate a Real Time Pricing (RTP) program, instead of, simply, curtail the wind. When using a RTP program, to increase consumption, the VPP is responsible for incentive the consumers to participate. Therefore, it is expected that in high wind situations, the energy price will decrease. The consumers' response is then obtained with the changes in the electricity price using an elasticity restriction. This measure can guarantee a better optimization of the wind farms, while it also establishes a development in the use of clean energies.

After this introduction, Section II presents the proposed methodology. In section III appears the mathematical formulation for the problem. Section IV describes the case study, and section V presents the results. Finally, section VI represents the conclusions of the paper.

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II. Developed Methodology

This section presents the proposed methodology and the main benefits of its use.

The proposed methodology was developed to be used by a VPP, an aggregator entity that is responsible for several types of distributed energy resources, such as DG, storages, demand response (DR) and electric vehicles [10]. For the present case study it was taken into consideration several types of energy resources like DG, prioritary (non-storable) and other (storable), external suppliers, water reservoirs and pumping. On the other hand, it were also applied programs to consumers such as: DR and RTP. Figure 1 outlines the proposed and developed methodology. It is important to enhance that the DG referred as prioritary, non-storable, as the case of wind power, solar and small hydro, are wasted if not used, however this generation has costs associated.

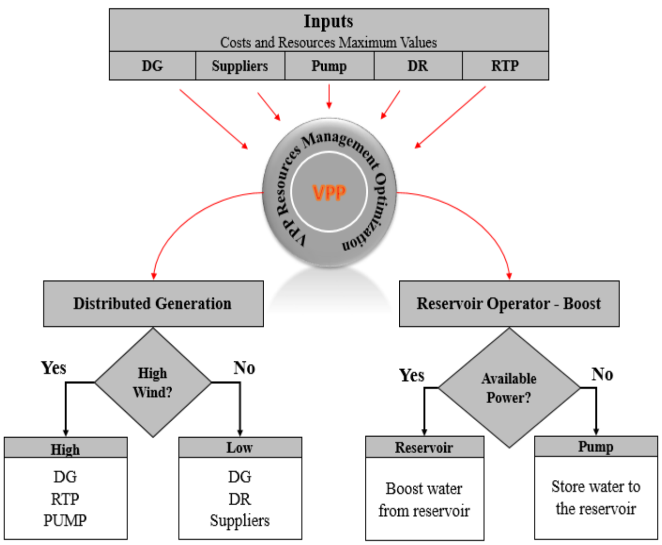

Figure 1 – Proposed methodology.

It is intended to maximize the implementation of renewable methods in the electric system, in this case the VPP would opt to pump water to the reservoir in situations when generation is higher than the demand.

The other resource, demand response, is divided into two distinct programs: Incentive based program (DR) and in price based program (RTP). The concept of DR, commonly defined as the modification of the electricity consumption pattern by end-use customers, in response to the variation in the electricity prices or to other signal related to technical or market operation issues, is currently an important research topic [11]-[12]. The RTP program is applied to all consumers that want to participate, as long as a valid contract between them and the operator exists. It envisages, in most cases, the increase of electricity demand, to try to seize all the power that is available in the electric network. In order to achieve a profitable solution for this leftover energy, the use of a VPP would lead to a real time pricing application that intends to match the demand to the forecasted generation. As said before, RTP is used, essentially, for the periods in which generation is higher than demand, so to incentive consumers to participate in this program, it is then expected that occurs a decrease in the energy price. This strategy is seen as innovative and interesting for all participants in this program, since it uses all the available energy, at a reduced price, mainly benefiting medium/large commercial or industrial consumers.

This work can contribute and be seen as innovative in the following situations:

- VPP usage to manage and dispatch the available resources according to situations of high or low wind, when compared to the demand. It is therefore oriented to small sized distributed resources;
- Water reservoir was considered to fulfill the reservoir operator requirements, along the case study, through the use of pumping;
- VPP operating costs minimization, when using resources such as DG and DR, including restraints that are applied to limit the influence of each available resource type;
- Implementation of a real scenario from the Portuguese power system, which represents a day of high wind power generation.

III. Mathematical Formulation

This section demonstrates the mathematical formulation developed in order to minimize the VPP optimization problem costs. The objective function is presented in (1) and it considers DG, External Suppliers, DR, RTP, Pump and Consumers. The DG, as described in the previous section, is divided into "prioritary" and "other", to separate the productions that need immediate processing, non-storable (e.g.: wind, solar, small hydro), from the ones that depend of fuel, storable (e.g.: Combined Heat and Power - CHP, Biomass, Municipal Solid Waste (MSW). The optimization problem was developed for 96 periods of 15 minutes.

$$Minimize\ VPP_{OC}$$

$$= \sum_{t=1}^{T} \left\{ \begin{array}{l} \sum_{g=1}^{G} \left[\begin{array}{l} (aP_{DG(g,t)}^{prioritary\ 2} + bP_{DG(g,t)}^{prioritary} \\ +cX_{iDG(g,t)}) \\ +(P_{DG(g,t)}^{other} \times C_{DG(g,t)}^{other}) \end{array} \right] \\ +\sum_{c=1}^{C} \left[\begin{array}{l} \left[\begin{array}{l} -(P_{load(c,t)}^{initial} + P_{RTP(c,t)}^{increase}) \\ \times(C_{load(c,t)}^{initial} - C_{RTP(c,t)}^{decrease}) \end{array} \right] \\ +(P_{DR(c,t)}^{reduction} \times C_{DR(c,t)}^{reduction}) \end{array} \right] \\ +\sum_{sp=1}^{Sp} \left[\begin{array}{l} (P_{Supplier(sp,t)}^{prioritary} \times C_{Supplier(sp,t)}^{prioritary}) \\ +(P_{Supplier(sp,t)}^{other} \times C_{Supplier(sp,t)}^{other}) \end{array} \right] \\ + \left[\begin{array}{l} (P_{(t)}^{Pump} \times C_{(t)}^{Pump}) \\ +(P_{(t)}^{EGP} \times C_{(t)}^{EGP}) \\ +(P_{(t)}^{NSP} \times C_{(t)}^{NSP}) \end{array} \right] \end{array} \right\} \quad (1)$$

In equation (1) the variable *a*, *b* and *c* denotes to the parameters of the quadratic function, on the other hand *P* represents the power, *C* the associated costs, *EGP* the excessed generated power and last, *NSP*, the non-supplied power. The following constraints are responsible for ensure that the VPP uses the available resources within the limits (maximum and minimum) stipulated, in order to satisfy all the demand required. The constraint given in (2) is the balance equation.

$$\sum_{G=1}^{G}[(P_{DG(G,t)}^{prioritary}+P_{DG(G,t)}^{other})] + \sum_{Sp=1}^{Sp}[(P_{Supplier(Sp,t)}^{prioritary}+P_{Supplier(Sp,t)}^{other})] = \sum_{C=1}^{C}[(P_{load(C,t)}^{initial}+P_{RTP(C,t)}^{increase}-P_{DR(C,t)}^{reduction})]+P_{(t)}^{Pump} \quad (2)$$

The consumers' behavior is modeled in equation 3, it represents the price elasticity of demand of each consumer. It can be applied to energy price variation according to the demand for different periods of the day, e.g., if the demand is high, so will it be the energy price and vice versa. The constraints presented (4) - (6), considers the DG maximum production capacity. In (5) the use of prioritary DG (non-storable), such as wind, solar or small hydro must be maximized.

$$\varepsilon = \frac{P_{Demand(c,t)}^{increase}\times C_{Demand(c,t)}^{initial}}{P_{Demand(c,t)}^{forecast}\times C_{Demand(c,t)}^{decrease}} \quad (3)$$

$$P_{DG(g,t)}^{prioritary}+P_{DG(g,t)}^{other}\le P_{DG(g,t)}^{Max} \quad (4)$$

$$P_{DG(g,t)}^{prioritary}+P_{EGP(g,t)}^{prioritary}=P_{DG(g,t)}^{prioritaryMax} \quad (5)$$

$$P_{DG(g,t)}^{other}\le P_{DG(g,t)}^{otherMax} \quad (6)$$

The equations (7) - (9) are related to external suppliers' maximum capacity.

$$P_{Supplier(sp,t)}^{prioritary}+P_{Supplier(sp,t)}^{other}\le P_{Supplier(sp,t)}^{Max} \quad (7)$$

$$P_{Supplier(sp,t)}^{prioritary}\le P_{Supplier(sp,t)}^{prioritaryMax} \quad (8)$$

$$P_{Supplier(sp,t)}^{other}\le P_{Supplier(sp,t)}^{otherMax} \quad (9)$$

The constraints (10) – (15) refer to the pumping process used in the optimization problem. The restriction presented in (11) obligates to occur only one action, or none, at a certain period. If it is pumping, the VPP opts to arise the level of the reservoir, so the reservoir owner can't turbine (boost) the water and vice-versa. Constraints (12) – (13) intend to limit the reservoir state within a maximum and a lower capacity value, whenever a pump or a boost process is going on. Both equations are concerned with the reservoir state in the previous period, *t-1*. In (14) is given a balance equation to determine the reservoir state, in a period t, it is then developed a relation between the reservoir level in the period before, t-1 with the processes that are happening in the period t, either pump or boost. The constraint (15) was considered to define an initial state for the reservoir, so when *t=0* it was assumed that was already water stored.

$$P_{(t)}^{reservoir}\le P_{(t)}^{reservoirMax} \quad (10)$$

$$P_{(t)}^{Pump}\le P_{(t)}^{PumpMax}, P_{(t)}^{Pump}=0 \ \ when \ \ P_{(t)}^{Boost}>0 \quad (11)$$

$$P_{(t)}^{Pump}+P_{(t-1)}^{reservoir}\le P_{(t)}^{reservoirMax} \quad (12)$$

$$P_{(t)}^{Boost}-P_{(t-1)}^{reservoir}\le P_{(t)}^{reservoirMin} \quad (13)$$

$$P_{(t)}^{reservoir}=P_{(t-1)}^{reservoir}+P_{(t)}^{Pump}-P_{(t)}^{Boost} \quad (14)$$

$$P_{(t=0)}^{reservoir}\le P^{reservoir\_InitialState} \quad (15)$$

In (16) it was considered DR, where it can be applied contracts to the electric system consumers. This type of program was applied, essentially, to two different types of consumers, domestic and small commerce, once these two represent the higher share of consumers. It is important to emphasize that for this particular case it were meant to be applied to the consumers.

$$P_{\mathrm{DR}(c,t)}^{reduction}\le P_{\mathrm{DR}(c,t)}^{reductionMax} \quad (16)$$

The remaining constraints (17) – (18) concerns the RTP program. It is also applied to the consumers, but it tends to focus in the increase of consumption, in periods where the generation is higher than the demand. Equation (17) relates to the total amount of power that the consumers can add to their initial consumption. Equation (18) represents the energy price that can be decreased from the initial one, depending on each consumer type.

$$P_{\mathrm{RTP}(c,t)}^{increase}\le P_{\mathrm{RTP}(c,t)}^{increaseMax} \quad (17)$$

$$C_{\mathrm{RTP}(c,t)}^{decrease}\le C_{\mathrm{RTP}(c,t)}^{decreaseMax} \quad (18)$$

IV. CASE STUDY

This section explains in detail the case study that was considered, in order to apply the proposed methodology. A real scenario using the Portuguese Power System has been implemented, referring to a special windy day, 9th March 2014, in which was possible to distinguish itself by the high generation coming from renewable resources when compared to the existing demand. To develop the optimization problem it was also taken into consideration the Feeder 5 electric network. This network is composed by 2223 consumers divided into five different types (Domestic (DM), Small, Medium (SC, MC) and Large Commerce (LC) and Industrial (IN)), 47 DG and, also considered, 10 external suppliers. To understand the capacity of the network used is important to emphasize that the demand resembles to 5384 kW, while the available DG corresponds to 3359 kW. The main objective in this paper, as was previously presented, is to present an optimal solution to deal with situations of high or low wind, aiming the VPP costs operation minimization.

The following tables, I and II, present the main parameters/characteristics from the producers and consumers that were considered to implement the optmization problem.

TABLE I. PRODUCERS CHARACTERISTICS.

	Distributed Generators	Generation cost (m.u./kWh)	N. Generation units	Installed capacity (kVA)
	Supplier	0,23 - 0,32	10	30000
Prioritary	Photovoltaic	0,15	18	610
	Wind	0,071	22	508
	Small hydro	0,042	2	7
	CHP	0,00106	0.9	1000
Other	Biomass	0,086	2	226
	MSW	0,056	1	8
	CHP	0,3	0.1	1000
	Pump	0,042	5	16

TABLE II. CONSUMERS CHARACTERISTICS.

Consumers Characteristics	DM	SC	MC	LC	IN
N. Consumers	1107	1083	8	9	16
Peak (kW)	780	777	851	746	2230
Elasticity	0,27	0,33	0,37	0,41	0,53
Initial Price (m.u./kWh)	0,21	0,18	0,20	0,19	0,15
Max. Power Increase (kW)	2340,4	6217,9	6810,9	5971,3	17844,9
Max. Price Variation	1,05	0,9	1	0,95	0,75
Max. DR Reduction (kW)	0,513	1,871	161,39	102,46	63,65
DR Costs (m.u./kWh)	0,2	0,16	0,19	0,18	0,14

The optimization problem was developed for the 24 hours of the day, but is divided in 96 periods of 15 minutes. When facing situations where the production overlaps the consumption (DG>Loads), the VPP may opt to pump to consume excess generation, storing water in the reservoir, or to encourage the consumers to increase their loads (RTP program), to prevent large energy losses in the power system.

The VPP will make use of the DR programs when different situations occur. DR will be applied to incentive consumers to decrease their loads, while the RTP, in periods in which the generation is higher than demand, will decrease the electricity price to incentive consumers to increase their demand, in order to maximize and avail the excess generation, as seen before. According to what was previously mentioned in section II, it is possible to complement that the VPP knew the periods in which the reservoir operator would opt to turbine the water, to generate electricity.

V. RESULTS

This section presents the results obtained when applying the base scenario to the developed methodology. It is important to point out that the results will pretend to focus, essentially, on the resources scheduling performed by the VPP. This base scenario is the day in study, a real scenario in the Portuguese power system, 9th March 2014.

A. Base Scenario

In order to present a detailed description of the obtained results, it has been selected an example scenario referred as base scenario. It corresponds to a real day in the Portuguese power systems, 9th March 2014. The figure 2, represents the 24 hours of that day, in 96 periods of 15 minutes.

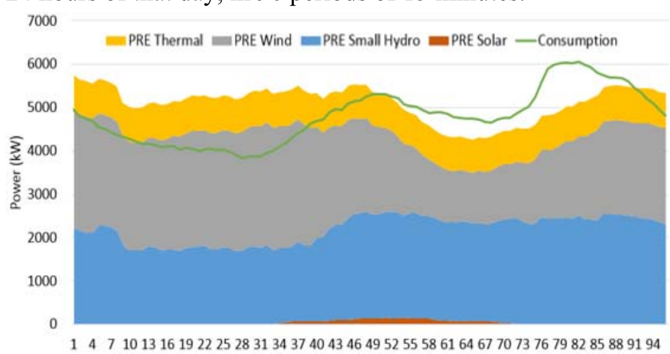

Figure 2 - Base Scenario, 9th March 2014 [13].

B. Resources Scheduling

This subsection demonstrates the results obtained by the VPP, when performing the resources scheduling. The generation will be dispatched according to the cost of each resource type, defined in the parameters.

For the morning periods (1-48) is possible to analyze, in figure 3, that the generation matches the consumption, is visible that the balance constraint is been applied and that the generation in excess was completely avoided, minimizing the electric system losses.

It is visible in the achieved results, that the VPP would always opt to ensures the maximization of the non-storable generation, as defined in the mathematical formulation, proving to be an efficient method according to what was initially stipulated.

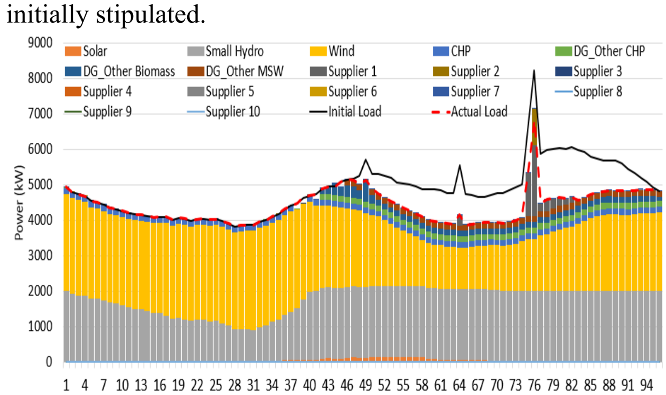

Figure 3 - Resources scheduling, along 96 periods.

In the second half of the day (49-96), according to figure 4, the reduction in demand is distinguishable, when comparing the *Initial Load* with *Actual Load*, it is possible to prove that the DR program was used and was effective for the purposes that it was used. On the other hand, the peaks visible in consumption refer to the pumping process that is being used to store water to the reservoir.

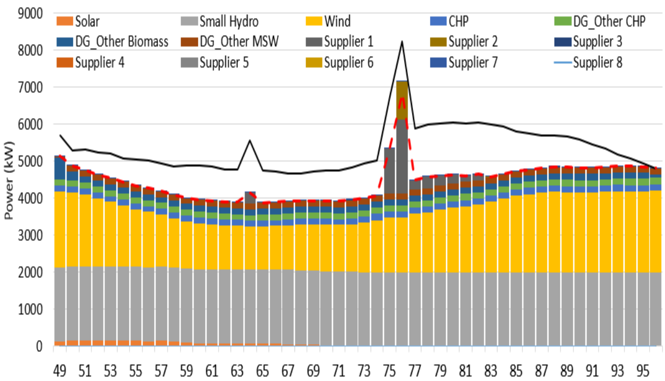

Figure 4 - Resources scheduling, in the afternoon till end of the day.

C. Pumping Process

The current subsection presents the results of pump used along the 96 periods of the day. As seen before, the purpose to use pump, in this problem, is to give the VPP an opportunity to store water to the reservoir, whenever it finds it to be more viable, in order to meet the reservoir operator demands. The reservoir operator will inform the VPP in which periods of the day he is going to turbine water, so that when those times occur, the VPP must ensure that the power needed is currently in the reservoir. The VPP can only be responsible to store water to the reservoir. As seen in the proposed methodology, the VPP can only manage small sized resources, like solar, wind, small hydro. In this case, the hydroelectric power plants that work with reservoir are not considered as small sized, so it was not possible to store water and to dispatch that power by using a VPP.

The obtained results are presented in figure 5. It is important to point that it was considered an initial state to the reservoir and in the following periods, is also noticeable the pumping being used, always to request the reservoir operator needs.

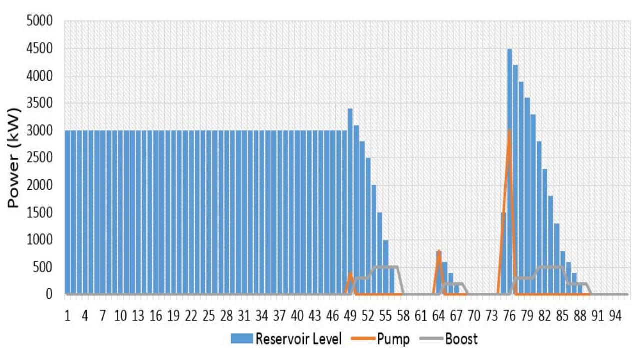

Figure 5 - Pumping process usage by the VPP.

VI. CONCLUSIONS

The methodology presented in this paper demonstrated that demand response programs proved to be an efficient method to apply as a response to the increasing penetration of distributed generation, which it may lead to new challenges in the way the electricity markets are operated. It was possible to present several benefits with the methodology used, like the application of real time pricing programs or water pumping to deal with high wind situations.

The use of an entity like the VPP proved to be efficient for the goals that were stipulated, in which is possible to underline the situations regarding the operation cost, which tends to be as lower as possible and through the resources scheduling aiming to equal the demand along the day. All these procedures can ensure that VPP is responsible to manage the power system efficiently.

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