

Optimal Management of a Virtual Power Plant

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Abstract— Deregulation of energy market led to the development of flexible and efficient framework for energy trading by energy companies in a competitive environment. Both deregulation and the concern towards environment issues increased the number of small and medium renewable power plants distributed in the network. The variability of renewable energy sources and the lack of their central monitoring led to new challenges concerning power system operation. The idea of aggregation for distributed energy sources led to the concept of virtual power plant, which determines a better control of production units but also a better visibility for the system operator. In this paper, the authors propose an optimal management solution which can offer a virtual power plant the capability to sell complete services, both for production and demand side management, by decreasing the necessary reserve for balance.

Index Terms—energy market, optimal management, renewable energy sources, virtual power plant.

I. INTRODUCTION

THE increased share of renewable energy sources in the electricity production brings issues concerning power balance in the power system. Generating electricity from renewable sources is influenced by weather conditions and by the availability of source – wind or sun. Using the power reserve of centralized sources is justified only from economic point of view. This reserve is used to compensate the shortage of energy determined by the unpredictable nature of renewable sources power generation. As a result, it seems more intelligent to transfer the balance load to another level of structure in the network. This structure should include different types of distributed resources, energy storage units and to have control and command rights.

All these can be combined in a structure like the virtual power plant (VPP) that can operate like a classical power plant. All operations for each unit can be programmed in advance. The concept of VPP has already a history of over two decades, experimental projects being tested in several parts of the world [1-4].

For the Romanian Power System, using the VPP as a solution for the management of renewable energy is not applicable yet; the solution used now considers including the renewable energy

sources (RES) in a large and diverse portfolio of a strong actor on the energy market.

II. MATHEMATIC MODEL

The optimization problem is actually a problem of maximizing the profit of the VPP [5], [6]. The aim is to maximize the profit for each and every one of the 24 hours:

$$profit = \sum_{t=1}^{24} (\lambda_t^{ISO} \cdot Bid_t + \lambda_t^{DR} \cdot R_t + \lambda_t^{VPP} \cdot D_t - E_t^{Disp} - y_t \cdot Start) \quad (1)$$

with constrains concerning:

- limits of the dispatchable generator:

$$E_t^{Disp} = a \cdot x_t + b \cdot G_t + c \cdot G_t^2 \quad (2)$$

$$x_t \cdot G^{\min} \leq G_t \leq x_t \cdot G^{\max} \quad (3)$$

$$-Ramp \leq G_t - G_{t-1} \leq Ramp \quad (4)$$

$$x_t - x_{t-1} \leq y_t \quad (5)$$

- energy balance equation:

$$G_t + W_t + S_t \leq D_t + Bid_t \quad (6)$$

- constrains concerning energy delivery:

$$\sum_{t=1}^{24} D_t = \sum_{t=1}^{24} (L_{it} - R_{it}) \quad (7)$$

$$D_t \geq 0.9 \cdot \sum_{t=1}^N (L_{it} - R_{it}) \quad (8)$$

$$D_t \leq 1.1 \cdot \sum_{t=1}^N (L_{it} - R_{it}) \quad (9)$$

- demand response (DR) constrains:

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$$R_{it} = L_{it} \cdot (1 - \exp(-\alpha_{it} \cdot (\lambda_t^{DR} - \lambda_t^{VPP}))) \quad (10)$$

$$\lambda_t^{VPP} \leq \lambda_t^{DR} \leq \lambda_t^{ISO} \quad (11)$$

$$\sum_{t=1}^{24} R_{it} > R^{\min} \quad (12)$$

where:

λ_t^{ISO} – forecasted price on the day-ahead market in the t period (€/MWh/h);

λ_t^{VPP} – contracted price inside the VPP during t period (€/MWh/h);

G^{max} – maximum production of dispatchable generator (MW);

G^{min} – minimum production of dispatchable generator (MW);

$Ramp$ – maximum ramp rate of the dispatchable generator (MW/min);

$Start$ – dispatchable generator starting costs (€);

W_t – forecasted wind production for t period (MW);

S_t – forecasted PV production for t period (MW);

L_{it} – forecasted load for consumer i for t period (MW);

D_t – forecasted demand for t period (MW);

α_{it} – elasticity price factor for consumer i in t period;

R^{\min} – minimum acceptable level for total load reduction (MW);

E_t^{Disp} – generation costs for dispatchable generator during t period (€/MWh/h);

G_t – output of the dispatchable generator during t period (MW);

λ_t^{DR} – price for demand side reduction during t period (€/MW);

$Profit$ – corresponding profit considering demand side reduction (€);

R_{it} – forecasted load reduction for consumer i during t period (MW);

Bid_t – hourly bid on energy market during t period (MW);

x_t – binary variable that indicate the state (operational/shut-down) of the dispatchable generator during t period;

y_t – binary variable that indicate if the dispatchable generator started during t period.

The objective function takes into consideration the VPP offers on the market, which can be positive or negative. Domestic consumers pay a fixed price according to bilateral agreements, λ_t^{VPP} equal to the levelized cost of energy (LCOE).

The constrains for the dispatchable generator (2-5) include the square cost function (2), minimum and maximum

generation levels (3), ramp up/down limits (4) and starting elements (5). The energy balance constraint (6) imposes the balance between the dispatchable generator production, the renewable sources production and consumption. An excess of generated power or stored energy gives the sign of the demand side on the market. The energy delivery constrains grant the necessary power covering all the demand. Some deviations, positive or negative, are included in (8) and (9). Also, for the delivery constrains, the demand reduction using DR are subtracted from the entire demand quantity. This model also presents the minimum aggregated demand reduction which can be accepted by the VPP (12). The reductions are not accepted when the entire quantity is smaller than the minimum acceptable level.

III. CASE STUDIES

All the presented case studies were conducted considering the entire Romanian Power System as a VPP, more exactly like a Bulk VPP (BVPP) [7], but with an arbitrary separation of each constituents of the VPP, in order to test and use all the integrated facilities of the *OptiMaCEV* application [6], including individual influence of each member of the BVPP.

The objective of the case studies was minimizing the financial losses (13) of the BVPP on the balancing market during 24 hours, losses which are determined by the errors between forecasted values for generation and real values of energy generation, errors which cannot be compensated by the DR.

$$FLoss = \sum_{t=1}^{24} (\Delta W_{prod} - \Delta W_{cons})_t \cdot \Delta \lambda_t^{BM} \quad (13)$$

where:

$\Delta \lambda_t^{BM}$ is the difference of energy price between the balancing market and day-ahead market during t period (€/MW);

ΔW_{prod} – deviation of real energy production from forecasted value;

ΔW_{cons} – deviation of real energy consumption from forecasted value.

Several case studies were conducted for different characteristic days, from different seasons and with different structure of the history used for the forecast. The first case study is based on history data from 25-30 August 2014 and the focus day is 31 august. The second case study uses data from 5, 12, 19, 26 June, 3, 10 and 17 July and the focus day is 24 July.

All the case studies are using real data from 2014 in order to compare the forecast results to real evolution of consumption and generation for each considered source. Meanwhile, real market prices were used, both from the day-ahead market and balancing market. Values for load category elasticity factors were used from literature. The data used to model the VPP were obtained from the Romanian Transmission System Operator – Transelectrica [8]. To compute the deviations of the forecast for

each VPP component and the VPP imbalance, the real value of the consumption was used. The computation relations are:

$$Ab = \frac{V_{prod} - V_{real}}{W_{cons_real}} \cdot 100[\%] \quad (14)$$

$$Dez = \frac{\Delta W_{prod} - \Delta W_{cons}}{W_{cons_real}} \cdot 100[\%] \quad (15)$$

where:

Ab – corresponding deviation for the considered value (consumption, classical power plant production, etc.);

V_{prog} – forecasted value (consumption, classical generation, wind generation, PV generation, etc.);

V_{real} – real value for the considered time period (consumption, classical generation, wind generation, etc.);

W_{cons_real} – real consumption value;

Dez – value of unbalance for the VPP as the result of deviation of forecasted values from the real ones.

IV. RESULTS AND DISCUSSIONS

A. Case Study #1

The results of interest for the forecasted (focus) day (on

hourly intervals) are presented in Table 1.

The results for Case Study #1 show high values of deviation for all hourly intervals for the classical power plant generation (22%), while for PV the values are practically null. This is due to the fact that the installed power in these plants is smaller compared to other energy sources (also see (14)).

For the consumption component of the VPP, the deviations values are big. It is important to be noted that by aggregating the generation and consumption components in the VPP, the deviations per component are compensated and for all the VPP the maximum value of deviation is 21% and only for a few hourly intervals.

Another fact to note is that for 1 to 8 hour interval, the positive deviation of VPP is a “consumption excess” type and requires a reaction to decrease the value of the load. To minimize the unbalances of VPP, the R reaction of demand reduction (completely or partially), is used as necessary. Reducing the value of the unbalances have a positive influence for the VPP profit due to the fact that any unbalance must be covered using the balancing market, where prices are least favorable than on the day-ahead market.

The unbalance on VPP can reach the value 0 after considering the demand response for hourly interval 9, 11 and 16 to 20, because the demand response was greater or at least equal with the necessary needed to bring the unbalance to 0.

TABLE I
VPP UNBALANCE FOR CASE STUDY #1 WITHOUT AND WITH DR

Hourly Interval	Classical Power Plant Deviation	Wind Deviation	PV Deviation	Consumption Deviation	Unbalance VPP	λ DR	R	λ ISO	Unbalance VPP with DR
1	8.2%	13.3%	0.0%	3.7%	17.8%	141.30	370.00	179.00	10.5%
2	11.8%	15.8%	0.0%	7.8%	19.7%	140.80	360.00	178.00	12.2%
3	9.8%	17.1%	0.0%	5.7%	21.2%	138.90	326.00	174.00	14.3%
4	12.2%	15.3%	0.0%	10.3%	17.2%	130.70	257.50	157.00	11.7%
5	12.7%	11.8%	0.0%	10.3%	14.2%	129.20	243.50	154.00	9.0%
6	12.0%	10.7%	0.0%	9.6%	13.1%	126.30	211.30	148.00	8.5%
7	18.0%	10.5%	0.0%	18.6%	9.8%	126.30	224.30	148.00	4.9%
8	8.2%	6.6%	-0.1%	8.0%	6.6%	126.80	249.70	149.00	2.0%
9	20.6%	5.5%	-0.6%	24.8%	0.7%	130.70	305.40	157.00	0.0%
10	22.6%	6.0%	-0.6%	30.4%	-2.4%	95.00	60.70	174.00	-2.4%
11	21.5%	7.4%	-0.4%	28.4%	0.0%	134.60	371.70	165.00	0.0%
12	20.0%	6.1%	0.0%	28.0%	-1.9%	95.00	64.50	168.00	-1.9%
13	17.4%	6.4%	0.2%	24.3%	-0.3%	95.00	63.00	157.00	-0.3%
14	19.7%	6.9%	0.2%	28.3%	-1.5%	95.00	65.40	154.00	-1.5%
15	20.8%	7.8%	-0.2%	29.7%	-1.4%	95.00	64.10	148.00	-1.4%
16	20.9%	7.2%	0.3%	27.5%	0.8%	121.80	213.40	139.00	0.0%
17	17.6%	7.9%	-0.5%	22.5%	2.5%	121.90	206.50	139.00	0.0%
18	2.8%	5.7%	-1.0%	3.7%	3.8%	129.20	295.00	154.00	0.0%
19	17.4%	6.6%	0.3%	22.4%	1.9%	134.60	367.60	165.00	0.0%
20	15.7%	4.0%	0.4%	19.4%	0.7%	135.90	422.60	174.00	0.0%
21	12.6%	2.4%	0.1%	17.6%	-2.6%	95.00	69.00	194.00	-2.6%
22	11.9%	2.7%	0.0%	16.9%	-2.4%	95.00	70.30	229.00	-2.4%
23	10.9%	2.3%	0.0%	14.9%	-1.7%	95.00	63.50	188.00	-1.7%
24	12.7%	4.0%	0.0%	15.9%	0.7%	141.80	425.00	180.00	0.0%

The balance price for the demand response, λ^{DR} for intervals 10 and 21-23 is smaller than the internal energy price for consumption, λ^{VPP} , and signals the necessity to stimulate the growth of internal consumption to reduce the unbalance. For all occurrences, the demand response was used to reduce the unbalance.

Another thing that is noted is the negative value of the deviation of VPP unbalance for interval 10, 12-15 and 21-23. This is a “low consumption” type, which means that is necessary a demand response in order to increase the

consumption, a signal given even by the demand response balance price.

Regarding minimizing the financial losses, from Table 2 it can be seen very clearly that using DR reduces supplementary costs determined by acquiring or selling energy to the balancing market during unbalance hourly intervals. The economy is about 844398.9 RON from 1448759.3 to 604360.4 RON.

The presented results also emphasize the fact that deviation of VPP when using demand response is the one who better attenuates the individual unbalance of their components.

TABLE II
DR INFLUENCE ON FINANCIAL LOSSES FOR CASE STUDY #1

Hourly Interval	Unbalance Δ without DR		Unbalance Costs [RON/MWh]		Supplementary Cost	Unbalance influence without DR		Unbalance Δ with DR	DR	Supplementary Cost	Unbalance influence with DR	
	[MW]	Excess	Deficit	[RON]	[RON/MWh]	[%]	[RON]	[MW]	[RON]	[RON/MWh]	[%]	
1	-906.91	5.38	198.00	118450.91	23.25	14.5%	-536.91	-370.00	83011.4	16.29	10.18%	
2	-950.73	39.57	243.49	92860.78	19.23	12.9%	-590.73	-360.00	64643.4	13.39	8.98%	
3	-999.23	0.10	213.78	128521.93	27.30	18.3%	-673.23	-326.00	100244.5	21.29	14.29%	
4	-801.29	0.10	214.62	64196.18	13.76	9.2%	-543.79	-257.50	80970.0	17.35	11.64%	
5	-662.18	0.10	213.12	18747.80	4.01	2.7%	-418.68	-243.50	63178.8	13.52	8.95%	
6	-605.25	0.10	221.68	1799.65	0.39	0.2%	-393.95	-211.30	66927.6	14.45	8.50%	
7	-446.25	0.10	251.69	11680.67	2.57	1.3%	-221.95	-224.30	44028.3	9.69	4.88%	
8	-360.72	0.10	258.83	14157.89	2.61	1.1%	-111.02	-249.70	25412.0	4.68	2.04%	
9	-32.54	0.10	306.95	50763.69	10.38	4.1%	0.00	-32.54	0.0	0.00	0.00%	
10	118.20	0.10	317.93	80914.05	16.38	7.0%	118.20	0.00	9920.8	2.01	0.86%	
11	-2.37	0.10	310.29	63125.76	12.52	6.0%	0.00	-2.37	0.0	0.00	0.00%	
12	97.05	0.10	290.83	54392.55	10.75	5.2%	97.05	0.00	8233.2	1.63	0.79%	
13	14.49	0.10	292.78	36625.46	7.19	3.5%	14.49	0.00	1230.2	0.24	0.12%	
14	76.41	0.10	304.85	58899.04	11.50	6.1%	76.41	0.00	8852.5	1.73	0.91%	
15	67.90	0.10	299.80	53363.86	10.65	5.6%	67.90	0.00	7523.2	1.50	0.79%	
16	-42.38	0.10	281.81	31384.22	6.22	3.3%	0.00	-42.38	0.0	0.00	0.00%	
17	-127.81	0.10	278.55	19984.04	3.93	2.1%	0.00	-127.81	0.0	0.00	0.00%	
18	-229.42	0.10	278.07	20381.66	3.38	1.8%	0.00	-229.42	0.0	0.00	0.00%	
19	-101.35	0.10	260.70	61196.76	11.70	7.7%	0.00	-101.35	0.0	0.00	0.00%	
20	-36.50	0.10	255.97	58790.76	10.89	5.9%	0.00	-36.50	0.0	0.00	0.00%	
21	150.53	0.10	259.25	91217.77	15.47	8.6%	150.53	0.00	11929.4	2.02	1.12%	
22	142.29	0.10	269.88	133859.31	22.16	14.9%	142.29	0.00	17200.5	2.85	1.91%	
23	94.73	0.10	235.70	106233.32	19.13	16.1%	94.73	0.00	11054.5	1.99	1.67%	
24	-37.83	0.10	232.78	77211.25	14.95	12.6%	0.00	-37.83	0.0	0.00	0.00%	

B. Case Study #2

The results of interest for the forecasted (focus) day (on hourly intervals) are presented in Table 3.

The results for Case Study #2 show deviation values smaller than 10% for the majority of hourly intervals, while for the PV the values are practically null.

For the consumption component of the VPP the deviation values are also smaller (with a maximum value of 14.6%), the large values appearing only in three intervals. Again, by aggregating the generation and consumption components in the VPP, the deviations per component are compensated and for all the VPP the maximum value of deviation is 12% and only for a few hourly intervals.

The positive values for deviation during 3-7, 9-13 and 15-24 hourly intervals is a “consumption excess” type and requires a

reaction to decrease the value of the load. To minimize the unbalances of VPP, the R reaction of demand reduction (completely or partially), is used as necessary. Also for this case, reducing the value of the unbalances have a positive influence for the VPP profit due to the fact that any unbalance must be covered using the balancing market, where prices are least favorable than on the day-ahead market.

For interval 2, 8 and 14, using DR the unbalance can be eliminated (the final value of the unbalance is 0) due to DR contribution – its availability was greater or at least equal with the necessary value to compensate the unbalance.

For this case study, only for the first hourly interval the deviation has a negative value – low consumption unbalance. This signals the fact that an increase of consumption reaction is needed.

TABLE III
VPP UNBALANCE FOR CASE STUDY #2 WITHOUT AND WITH DR

Hourly Interval	Classical Power Plant Deviation	Wind Deviation	PV Deviation	Consumption Deviation	Unbalance VPP	λ^{DR}	R	λ^{ISO}	Unbalance VPP with DR
1	0.2%	3.7%	0.0%	4.4%	-0.5%			149.0	-0.5%
2	0.0%	4.6%	0.0%	3.6%	1.0%	116.9	131.9	129.0	0.0%
3	-12.7%	3.9%	0.0%	-13.1%	4.3%	112.0	73.5	119.0	3.1%
4	2.4%	2.2%	0.0%	4.1%	0.6%	107.0	21.3	109.0	0.1%
5	0.0%	1.8%	0.0%	1.0%	0.8%	107.0	20.9	109.0	0.4%
6	-0.3%	5.2%	0.0%	0.7%	4.2%	109.3	44.7	113.6	3.3%
7	1.3%	4.9%	0.0%	3.1%	3.1%	116.9	131.7	129.0	0.7%
8	1.4%	3.4%	0.2%	1.7%	3.2%	129.2	288.3	154.0	0.0%
9	0.3%	5.0%	0.5%	-1.3%	7.1%	139.4	437.9	175.0	0.4%
10	-1.6%	6.2%	0.9%	-3.7%	9.2%	141.3	463.7	179.0	2.3%
11	0.3%	6.3%	0.8%	-0.8%	8.2%	141.3	479.1	179.0	1.1%
12	1.6%	7.2%	1.0%	1.0%	8.7%	141.3	489.3	179.0	1.5%
13	-10.1%	6.2%	-0.4%	-14.6%	10.3%	141.3	482.6	179.0	4.1%
14	3.8%	6.8%	-0.4%	3.8%	6.3%	141.3	507.9	179.0	0.0%
15	-0.1%	5.7%	-1.1%	-1.9%	6.3%	136.5	417.7	169.0	0.2%
16	1.6%	5.1%	-0.1%	0.4%	6.3%	131.1	344	158.0	1.1%
17	-0.3%	8.5%	-0.4%	-2.3%	10.0%	131.1	340.2	158.0	4.9%
18	0.2%	10.6%	-0.4%	-1.2%	11.5%	136.5	408.5	169.0	5.4%
19	-0.3%	10.5%	-0.1%	-1.5%	11.7%	136.5	403.2	169.0	5.5%
20	0.2%	9.3%	-0.2%	-0.9%	10.2%	136.5	405.7	169.0	4.0%
21	5.7%	10.3%	0.0%	6.3%	9.8%	136.5	441	169.0	3.2%
22	2.7%	8.6%	0.0%	2.0%	9.3%	136.5	438.8	169.0	2.9%
23	-9.5%	5.7%	0.0%	-14.3%	10.6%	129.2	321.3	154.0	6.5%
24	2.5%	8.6%	0.0%	2.7%	8.4%	129.2	299.9	154.0	3.5%

TABLE IV
DR INFLUENCE ON FINANCIAL LOSSES FOR CASE STUDY #2

Hourly Interval	Unbalance Δ without DR		Unbalance Costs [RON/MWh]		Supplementary Cost	Unbalance influence without DR			Unbalance Δ with DR	DR	Supplementary Cost	Unbalance influence with DR	
	[MW]		Excess	Deficit		[RON]	[RON/MWh]	[%]				[RON]	[MW]
	1	29.4	30	344		4369.5	32.74	16.8%	29.38	0.00	4369.5	0.78	0.40%
2	-51.4	34.26	356.78		7858.5	32.25	17.2%	0.00	-51.36	0.0	0.00	0.00%	
3	-262.5	75.79	394		24435.9	27.99	16.6%	-188.97	-73.50	17593.0	2.90	1.72%	
4	-28.8	50.22	384		3448.8	41.21	24.2%	-7.50	-21.30	897.7	0.18	0.10%	
5	-42.0	77.04	390		4026.3	40.32	23.3%	-21.10	-20.90	2022.8	0.39	0.23%	
6	-217.3	67.4	390		26899.0	26.65	13.9%	-172.60	-44.70	21365.6	4.12	2.16%	
7	-168.8	67.51	400		23682.3	29.36	14.1%	-37.11	-131.70	5206.2	0.97	0.47%	
8	-187.2	78.1	431		30863.5	29.69	12.2%	0.00	-187.15	0.0	0.00	0.00%	
9	-460.8	30	407		101829.6	16.29	6.5%	-22.87	-437.90	5053.7	0.78	0.31%	
10	-616.7	30	415		136285.6	9.73	3.9%	-152.98	-463.70	33807.9	5.05	2.01%	
11	-551.8	30	413		118630.7	9.98	4.1%	-72.67	-479.10	15624.2	2.33	0.95%	
12	-588.9	30	408		122490.1	6.82	2.9%	-99.59	-489.30	20715.7	3.08	1.29%	
13	-806.7	30	400.28		169403.4	1.23	0.5%	-324.12	-482.60	68062.2	8.67	3.61%	
14	-430.4	30	401		83920.1	9.66	4.3%	0.00	-430.36	0.0	0.00	0.00%	
15	-431.9	30	380		81626.1	6.66	3.0%	-14.18	-417.70	2680.8	0.39	0.18%	
16	-415.7	30	382		73169.7	6.10	3.0%	-71.74	-344.00	12625.7	1.91	0.93%	
17	-670.3	30	378		117976.4	2.42	1.2%	-330.12	-340.20	58101.2	8.67	4.21%	
18	-764.0	30	381		148974.0	4.79	2.1%	-355.47	-408.50	69316.5	10.48	4.66%	
19	-765.0	30	388		152235.1	1.42	0.6%	-361.80	-403.20	71998.3	10.98	4.80%	
20	-669.6	30	399		140612.3	6.08	2.5%	-263.91	-405.70	55419.3	8.46	3.52%	
21	-651.0	30	405		143865.5	8.57	3.4%	-209.98	-441.00	46404.5	6.99	2.78%	
22	-636.8	30	413		140731.2	10.11	4.0%	-197.99	-438.80	43756.4	6.36	2.53%	
23	-826.0	30	411		161060.4	2.92	1.3%	-504.65	-321.30	98406.9	12.62	5.61%	
24	-512.9	30	333		92329.3	3.72	1.8%	-213.04	-299.90	38347.3	6.31	3.01%	

Regarding minimizing the financial losses, from Table 4 it can be seen very clearly that using DR reduces supplementary costs determined by acquiring or selling energy to the balancing market during unbalance hourly intervals. The economy is about 1418947.9 RON from 2110723.3 to 691775.4 RON.

V. CONCLUSION

Implementing the concept of VPP, determine the growth of power system benefits, due to using more efficient the distributed generation units, hence a greater operation efficiency. In this case, distributed generation can become more visible, can have a better access to energy markets and also can maximize the opportunities regarding incomes from selling the energy and reducing the environment pollution by using fewer classical power plants. The VPP can be considered an observable instrument for optimal solving of renewable energy sources integration and the case studies presented emphasize this aspect.

The results from the case studies prove that including the original elements in the VPP management - meaning considering the level of BVPP and the level of additional optimization by minimizing the financial losses due to acquiring energy from the balancing market, is justified and leads to better performance for the VPP.

Even more, it is again confirmed the fact that the VPP can be the favorable element in the power grid evolution towards "smart grid".

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