Impact of Production from Photovoltaic Power Plants on Increase of Ancillary Services in the Czech Republic

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Abstract. *Renewable energy resources represent a noticeable part of the overall energetic concept development. New integration of renewable energy resources into power grids has a significant impact on the reliability and quality of power supply. The major problem of the photovoltaic and wind power plants is their dependency on weather conditions, since it has a direct effect on their immediate output produced that shows stochastic behaviour. These stochastic outputs result in very adverse impacts on the power grid. Further development of these resources could lead to exceeding of the control and absorption abilities of the power grid. The power grid must be set in balance with respect to the production and consumption of electric power at any time. The operation of photovoltaic power plants impair keeping this balance. That has an adverse impact on the very operation and maintenance of network parameters within the extent required. This survey deals with analysis focused on operation of the photovoltaic power plants with respect to the increase of reserve power in ancillary services in the Czech Republic.*

Keywords

Ancillary services, calculation methodology, computing applications, photovoltaic power plant, real measurement, statistical methods.

1. Introduction

Both photovoltaic power and wind power are sources considerable depended on meteorological conditions [5], [6], [10]. The survey is based on the article [4] with detailed description of the draft methodology for computing of extreme conditions in Photovoltaic Power Plants (PvP). This article elaborates on the survey with draft methodology to assess the increase of reserve power in ancillary services with respect to operation of PvP. These methodologies are then applied to real data collected during operation of the specific PvP and to the actual data of energy regulatory. This analysis shows the period of rapid increase of photovoltaic output across the power grid of the Czech Republic (CZ). The final parts provide definition of output increase to be delivered with respect to the impact of PvP operation on the existing ancillary services MZ15+ (15 minute positive back-up) and MZ15- (15 minute negative back-up) [3]. This is already the case nowadays.

It was elaborated many studies focused on the prediction of photovoltaic and wind power plants such as [7], [8], [9]. This survey differs from others in that it does not predict anything but based on the actual situation.

2. Ancillary Services

The Czech Power Grid Code, Part II [3], approved by the Energy Regulatory Office, defines the method for utilisation of the power grid with respect to ancillary services. One of the prerequisites for determination of summary regulatory backups of ancillary services is the deviation $OD_{RES(t)}$. This is a parameter to establish the increment of balancing deviation caused by production from newly installed renewable resources to electric power. As stated here Eq. (1), this increment is defined by the sum of increase generated by operation of wind $OD_{VtE(t)}$ and photovoltaic $OD_{FVE(t)}$ power plants. The deviation $OD_{RES(t)}$ is then used to determine volumes of ancillary services required for the subsequent period [3]:

$$OD_{OZE(t)} = OD_{VtE(t)} + OD_{OZE(t)}. \quad (1)$$

Equation (1) implies that the effect of installed capacity of PvP has a certain impact on calculation of ancillary services. This fact initiated elaboration of this survey.

The impact brought by increase of the installed capacity of PvP on remote control of the power grid and the relevant utilisation of Ancillary Services (AS) could be observed since the year 2011, when the installed capacity of PvP grew from approximately 450 MW in the preceding year to approximately 1950 MW in this year [2].

The period from 2010 to 2012 showed an increase of the system output deviation. The system deviation is used for assessing the surplus or lack of electric power in the grid. The standard deviation of this system deviation then grew by up to 50 MW during afternoon hours to reach the extreme value of approximately 200 MW [2]. The reason for this increase may be the effect of PvP, as prediction models applicable to production of electric power by PvP cannot provide an accurate estimate of the weather effects on commissioning of production using these resources. The outcome from prediction models has a direct effect on behaviour of market players, including determination of system deviation.

3. Extreme Conditions of PvP

The very assessment of extreme conditions of PvP is based on the annual monitoring of a specific photovoltaic power plant at the break of 2010/2011. The PvP with peak power output of 1.1 MWp subject to measurement here is connected to the power grid and it represents a sole resource in the network during the measurement period. As far as topology is concerned, this grid is looped, although operated as a radial one [1].

The assessment methodology is based on values obtained from average five-minute outputs. When compared to the above mentioned article published earlier, we have performed slight changes to statistical regressions of extreme conditions of PvP, yet the principles of this assessment have remained the same.

3.1. Maximum Extreme Conditions

The result produced by methodology for assessment of maximum extreme conditions of PvP comprises the Gauss's equation with parameters A, B, C and D for each month of the year for the best approximation of these maximum values. This formula is generally expressed as follows [7]:

$$f(x) = A \cdot e^{-\frac{(t-B)^2}{2 \cdot C^2}} + D, \quad (2)$$

where A, B, C and D are parameters of Gauss's equation.

The general function of Gauss's equation can be applied to the output curve showing maximum extreme conditions as follows (e.g. for April):

$$P_{FVE\,\max} = -1274810 \cdot e^{-\frac{(t-0.4928263)^2}{2 \cdot 0.17422^2}} + 383794, \quad (3)$$

where $P_{FVE\,\max}$ is maximum extreme condition of PvP (W), t is time (hh:mm).

When assessing other values of peak output from PvP, one has to multiply the parameter "A" from Eq. (2) with the relevant value determined by the ratio of peak output from another PvP to the peak output of this PvP (1.1 MWp).

The time t and time lines for graphic results are always defined in the so-called Universal Time Coordinated (UTC). Conversions between the UTC and the Central European Time (CET) or the Central European Summer Time (CEST) are defined by Eq. (4) and Eq. (5). However, it is necessary to bear in mind that MS Excel converts the time data into numerical values. That means time is represented by decimal numbers from 0.0 to 1.0 (0.00 to 24.00 o'clock). For example, the numerical value 0.5 is matched by time 12.00 o'clock [3], [6].

$$t_{cet} = \frac{h_{utc} \cdot 60 + m_{utc}}{1440} + \frac{1}{24}, \quad (4)$$

$$t_{cest} = \frac{h_{utc} \cdot 60 + m_{utc}}{1440} + \frac{2}{24}, \quad (5)$$

where t_{cet} is Central European Time, t_{cest} is Central European Summer Time, t_{utc} is Universal Time Coordinated, h_{utc}/m_{utc} is value of hour/minute according to UTC.

Tab. 1: Parameters of Gauss's equation of maximum extreme conditions of PvP for individual months of the year.

Months	Parameters of Gauss's Equation			
	A	B	C	D
1	-3600950	0.49921	0.262209	2932140
2	-2089680	0.503123	0.211292	1317490
3	-1956580	0.499046	0.223049	1112310
4	-1274810	0.4928263	0.17422	383794
5	-1357560	0.4936243	0.188437	440029
6	-1180160	0.4983373	0.18539	307280
7	-1180020	0.5057943	0.188995	338914
8	-1384590	0.5036093	0.198893	535948
9	-2212550	0.4949763	0.252074	1389050
10	-5041080	0.4860943	0.367736	4274150
11	-3235550	0.484282	0.268296	2548530
12	-299418	0.484282	0.0412953	-64029.2

For individual parameters of Gauss's Eq. (2) for particular months of the year see the Tab. 1. Similarly to the Eq. (3) for April, these parameters are inserted into the Eq. (2) to determine the curve of maximum extreme conditions of each month.

Maximum extreme conditions of PvP production are described by the Fig. 1 and Fig. 2. Figure 1 includes months in the period from December to June. The courses of individual curves show full match provided the results depend on intensity of solar radiation, the duration of sunshine during the day and the impact of temperature of solar panels. One can observe that the dispersion of production time is extended proportionally to the increasing duration of sunshine within particular months and the amplitude is rising with increasing intensity of solar radiation. The maximum occurs in May rather that during the summer solstice, as might be expected. That is due to the impact of direct proportion between panel efficiency and temperature.

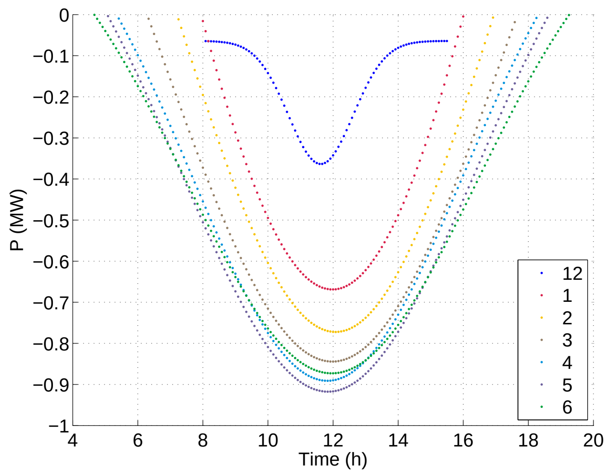

Fig. 1: Regression curves of maximum extreme outputs for individual months (December to June).

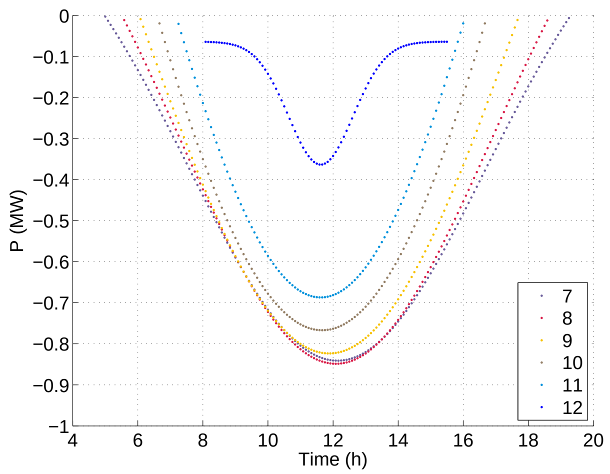

Fig. 2: Regression curves of maximum extreme outputs for individual months (July to December).

The panel efficiency drops proportionally to the rise of its temperature. Figure 2 shows the maximum extreme curves from July to December, i.e. between the summer and winter solstice. There was also a minor sign of higher panel temperature in July, when compared to August, it means a greater extreme reached in August.

3.2. Minimum Extreme Conditions

Although the visual assessment of graphic illustration of production from PvP showed evident certain proportion of the diffusion element of radiation, the objective determination of their overall share is very difficult. Accurate assessment would require measurement of the ratio between the direct and diffusion elements of radiation that was not subject to measurement. Approximation of minimum extreme conditions in production by means of a constant function equal to zero is not a convenient approach either, since the graphic output shown by Fig. 3 expresses an evident share of the diffusion radiation element and it needs to be respected. It is therefore necessary to determine this threshold of minimum extreme conditions by other means to respect the diffusion radiation element that is 100 % identifiable upon visual inspection of the Fig. 3. To serve the purpose of this survey, the share of diffusion radiation element has been defined as the so-called guarantee share of diffusion radiation element. This information provides far better informative value about the minimum production at PvP than the sole diffusion radiation element. That is due to the fact it reflects the actual condition of PvP operation with respect to the minimum production, i.e. both the diffusion and direct elements. Figure 3 shows the scatter chart with one-minute outputs per specific month for the year 2010 with clear evidence of the guaranteed diffusion radiation. It is located in the area missing any output values. There is not even one value observed in this field under

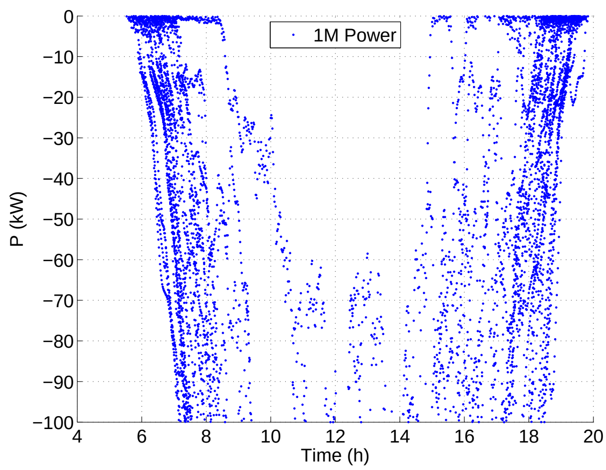

Fig. 3: Guaranteed share of diffusion radiation.

the specific circumstances. That is why this field can be defined as the guaranteed share of diffusion radiation.

Assessment of the minimum extreme conditions follows the same methodology applied in case of the maximum extreme conditions of production delivered by PvP. The outcome from assessment of the minimum extreme conditions of PvP is the Gauss's curve once again; it provides convenient approximation of these minimums. The Gauss's equation of the curve expressing the minimum extreme conditions of production from PvP for April 2011 is defined as:

$$P_{PvP\,\mathrm{min}} = -124533 \cdot e^{-\frac{(t-0.494557)^2}{2\cdot 0.100209^2}} + 1201.97, \quad (6)$$

where $P_{PvP\,\mathrm{min}}$ is minimum extreme condition of PvP, t is time (hh:mm).

Same as for regression curves of the maximum extreme conditions, even this equation refers to t defined by the so-called Universal Time Coordinated (UTC). Conversions between the UTC and the Central European Time (CET) and the Central European Summer Time (CEST) are defined by the above mentioned Eq. (4) and Eq. (5).

For individual parameters of Gauss's Eq. (2) for specific months of the year see the Tab. 2. Same as in the Eq. (6) for April, these parameters are inserted into the Eq. (2) to plot the curves of minimum extreme conditions of PvP.

Tab. 2: Parameters of Gauss's equation of minimum extreme conditions of PvP for individual months of the year.

Months	Parameters of Gauss's Equation			
	A	B	C	D
1	-65199.2	0.498540444	0.0941881	14166
2	-123893	0.501989222	0.127915	38423.7
3	-115800	0.499487444	0.12374	10454.8
4	-124533	0.494557	0.100209	1201.97
5	-144600	0.491698444	0.120717	3399.95
6	-151374	0.500168	0.146449	12303.4
7	-118188	0.508342667	0.142813	8777.12
8	-104815	0.503144778	0.11419	1134.17
9	-96112.4	0.496590778	0.101559	594.665
10	-89190.1	0.485495667	0.127737	18992.3
11	-60925.1	0.507583	0.123552	20331.2
12	-18368	0.513792	0.0529752	2237.18

For graphic illustration of the minimum extreme conditions of production from PvP, see the Fig. 4 and Fig. 5. Figure 4 includes months from December to July. The course of individual curves matched as expected, depending on the intensity of solar radiation, yet they would not match with respect to duration of sunshine. That was due to the insufficient size of database with the data measured. To suppress the negative impact, curves for particular months were centered against one another at the same ratio as for

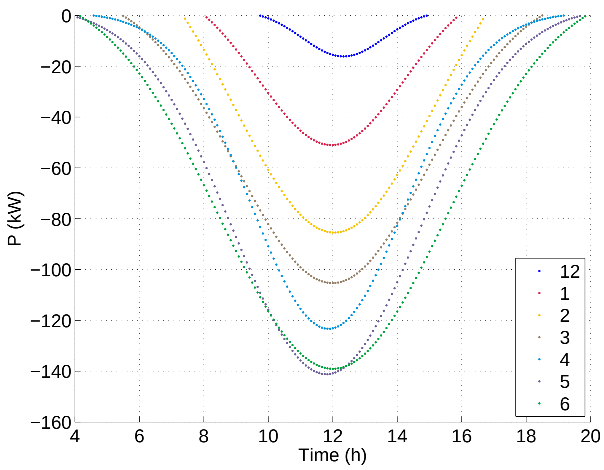

Fig. 4: Regression curves of minimum extreme outputs for individual months (December to June).

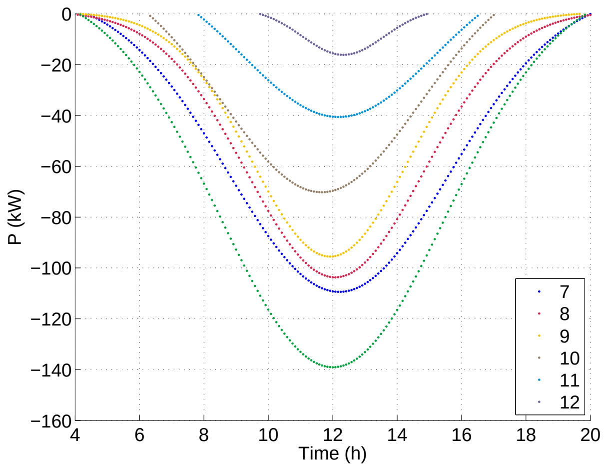

Fig. 5: Regression curves of minimum extreme outputs for individual months (July to December).

curves showing the maximum extreme conditions. Figure 5 illustrates the maximum extreme curves from July to December. Even these have been changed accordingly with respect to the maximum extreme conditions.

The defined maximum and minimum extreme conditions of PvP approximated by the relevant regression curves can be used to establish the difference between these two curves. This is called the difference of active power from PvP and it differs for each month or time interval. This survey concerns one-hour intervals. These results are vital for optimisation of control outputs for ancillary services, for more details see next Section 4.

4. Analysis of Output Deviation Changes in the Power Grid of Czech Republic

The period from 2009 to 2013 brought a significant increase of the installed capacity of photovoltaic output within the power grid in CZ. The rising number of these resources with stochastic output also leads to interference with the capacity balance between the immediate production and consumption of electric power. That results in an increase of the system output deviation as well as deviations of regulatory energy to cover this capacity imbalance. The system deviation defines the immediate difference between the electric power produced and consumed across the power grid, whereas deviations of regulatory energy represent the amount of reserve power used, mainly by ancillary services, to cover the deflection of the system deviation. Keeping the system output deviation in balance is necessary to ensure safe and reliable operation of the power grid and maintenance of specified standards.

4.1. Dependency of System Deviation on the Installed Capacity of PvP

The first step is to prove the dependency between the increase of system deviation and the rise of installed capacity of PvP. This assessment has been carried out using data from hourly averages of the system deviation as well as the data referring to installed capacity of PvP within the territory of Czech Republic to 31st December each year during the period from 2008 to 2012 [3]. This assessment is based on correlation analysis of the increase of the system deviation and the increase of installed capacity of PvP. Those are the following parameters:

- SyS_{diff} - relative maximum daily difference of system deviation,
- $p_{inst.}$ - relative installed capacity of PvP for each year to 31st December 2013.

The relative maximum daily difference of the system deviation has been defined as the ratio between the maximum daily differences of system deviations with hourly averages during the individual years from 2009 to 2014 and the top value of maximum daily difference throughout the observed period. The relative installed capacity of PvP represents a simple ration of installed capacity with respect to the top value of installed capacity during the observed period. For correlation between these curves refers to the Fig. 6.

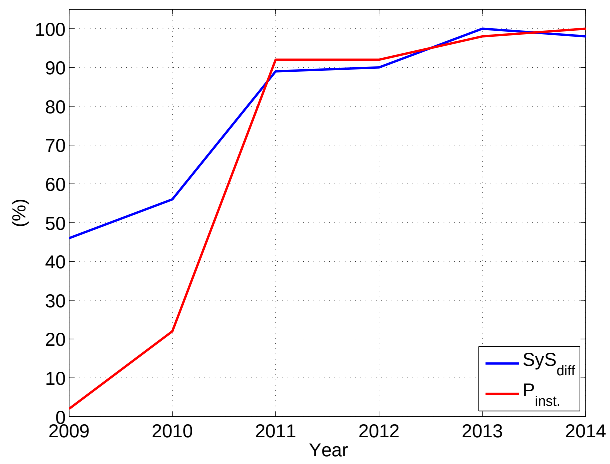

Fig. 6: Correlation of the relative increase of system deviation difference and the installed capacity of PvP.

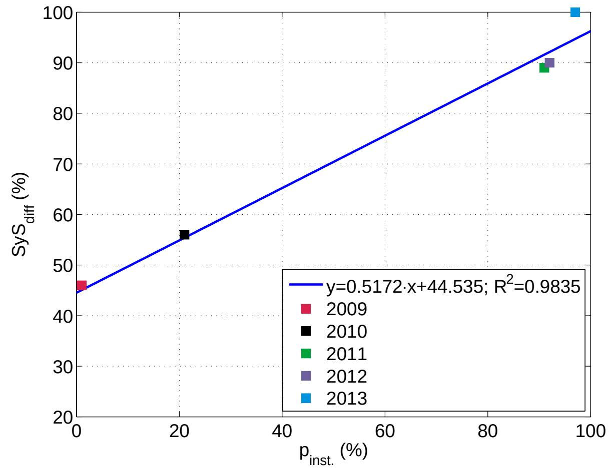

Fig. 7: Correlation analysis of the difference in system deviation and installed capacity of PvP.

There is an evident correlation between these curves based on the visual evaluation. The annual increase of new installed capacity in the power grid results in rise of the relative difference of system deviation. To rule out any speculation regarding the visual evaluation, these parameters have been subject to correlation analysis, see Fig. 7. The most convenient regression is the linear regression with determination index R^2 over 98 %, which proves that the selected regression model is correct. There is a very strong dependency.

This Subsection 4.1. provides clear evidence of changes to system deviation depending on operation of PvP.

4.2. Analysis of Regulatory Deviations

This chapter deals purely with the change to control energy that has a direct effect on provision of ancillary

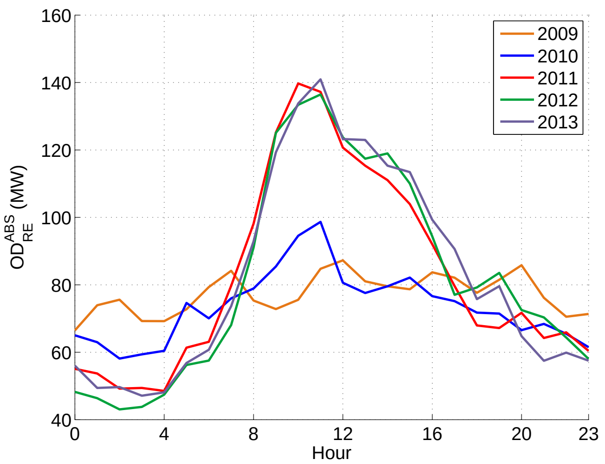

Fig. 8: Hourly course of absolute values of regulatory energy in particular years.

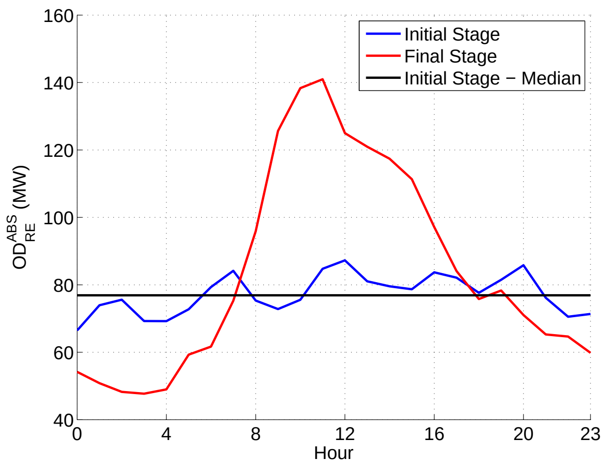

Fig. 9: Course of regulatory energy, initial and final stages.

services. The aim is to enumerate the increase of regulatory energy in relevance with the rise of photovoltaic output.

The average hourly course of absolute values of regulatory deviations in particular years from 2009 to 2013 is presented by Fig. 8. Those are average values of output really used to cover the imbalance between production and consumption of electric power. That reflects the actual intervention of power grid operators with this fact; it has a direct impact on procurement of ancillary services.

The optimal type of service purchased for balancing of capacity in this situation is the Positive Minute Regulatory Back-Up achievable within 15 minutes (MZ15+) together with the Negative Minute Regulatory Back-Up achievable within 15 minutes (MZ15-) [3]. It has been concluded pursuant to professional consultation with personnel from the Czech Energy Transmission System and observation of the nature of data considered with respect to regulatory energies.

The objective is to define a specific value for capacity increase in the ancillary service MZ15+ and MZ15-. The assessment methodology is based on comparison of imbalance of regulatory energy depending on gradual integration of photovoltaic power plants within the power grid in CZ.

The sole assessment is highly restricted to the data available. That is defined by the method for connecting PvP to the power grid. There has actually been a jump increase of these resources within one to two years only; followed by further decay that brings a serious impairment to detailed analysis of this issue. Another fact to be considered is the change to both production from PvP as well as the daily load diagram with direct impact on regulatory energy values.

Same as for PvP, even this issue has been evaluated with respect to the optimal period of one month. The limited amount of data restricts the option to determine the evaluation methodology pursuant to data for individual months. That is why the draft of this methodology is based on annual average data to be applied on the data for particular months later on.

Figure 8 shows the course of absolute values of regulatory energy over the observed period. The course details for years 2011, 2012 and 2013 do not show any statistical difference. That is because the magnitude of installed capacity of PvP in the power grid is almost identical. Further assessment will be carried out with an average of these three years, while the resultant values will explain the increase of system deviation caused by operation of PvP. It is the so-called final stage, as far as this survey is concerned. The year 2009 represents the period, when the impact of PvP operation on the installed capacity was very low and it stands

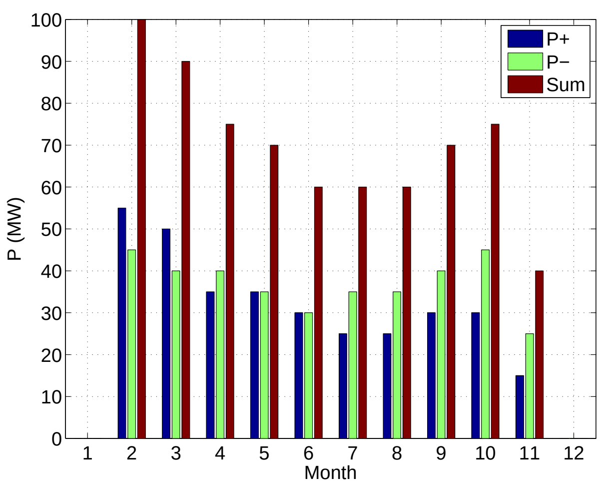

Fig. 10: Monthly values of positive and negative values of the regulatory output.

Tab. 3: Values of increase of the ancillary service MZ15+ and MZ15- with respect to PvP.

Months	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
4:00	0/0	0/0	0/0	0/0	5/5	0/0	0/0	0/0	0/0	0/0
5:00	0/0	0/0	0/0	5/5	5/5	5/5	5/5	0/0	0/0	0/0
6:00	0/0	10/5	10/10	10/10	10/10	10/10	5/5	10/10	5/10	0/0
7:00	10/10	20/20	20/20	15/15	15/15	10/15	10/15	15/20	15/20	5/10
8:00	20/20	35/30	35/30	25/25	20/20	15/25	15/20	25/30	20/30	10/15
9:00	40/35	45/35	40/35	30/30	25/25	20/30	20/30	25/35	25/40	10/20
10:00	50/40	50/40	45/40	30/35	30/30	20/30	25/30	30/40	30/40	15/25
11:00	55/45	50/40	50/40	35/35	30/30	25/35	25/35	30/40	30/45	15/25
12:00	55/45	50/40	50/40	35/35	30/30	25/35	25/35	30/40	30/40	15/25
13:00	50/40	50/40	50/40	30/35	30/30	25/35	25/35	30/40	25/40	15/25
14:00	40/35	45/35	45/40	30/30	25/25	20/30	20/30	25/35	20/35	10/15
15:00	20/20	35/30	40/35	20/25	20/20	20/25	15/20	20/30	15/25	5/10
16:00	5/5	25/20	30/25	15/15	15/15	15/20	10/15	15/20	10/10	5/5
17:00	0/0	10/10	20/15	10/10	10/10	10/15	5/10	5/10	0/0	0/0
18:00	0/0	0/0	5/5	5/5	5/5	5/10	5/5	0/0	0/0	0/0
19:00	0/0	0/0	0/0	0/0	5/5	5/5	0/0	0/0	0/0	0/0

for the so-called initial stage. The distribution of data shows a clear tendency towards convergence to a constant value. That is why the initial stage values will be replaced with its median.

The difference between extreme of the final stage curve and the initial stage curve (median) represents the change in increase of regulatory energy over the observed period. This value represents the maximum absolute value of regulatory energy, for more details refer to Fig. 9.

This methodology is applied to individual months of the year to determine the maximum absolute values of regulatory energy. These absolute values are further divided to positive and negative regulatory energies. The division is based on database of regulatory energy data for the year 2013, with definition of the ratio between the positive and negative regulatory energies. The absolute values of regulatory energy for individual months were further divided proportionately.

The outcome has been plotted in the column chart shown by Fig. 10 that defines the increase of ancillary services for individual months due to integration of PvP. The worst impact of PvP was experienced in February. That is due to the fact that the weather change in that period is dynamic, resulting in significant demands to keep the balance between production and consumption of electric power. Similar weather can be also expected for September and October showing greater increase of regulatory energy. The paradoxically lowest demand for support to ancillary services with respect to operation of PvP comes during summer months. That is due to the more stable nature of weather, when the production from PvP is easier to predict. The winter months did not prove any dependency between production from PvP and ancillary services, since the production from PvP is generally lower during winter, while the load curve rises significantly. It means the share of PvP on increase of ancillary services is very small.

4.3. Optimisation of Regulatory Energy

The current data shows the increase of regulatory energy for individual months as constant throughout each day. However, this is not wise when considering the distribution of production delivered by PvP, since the change of production from PvP during the day must be paralleled by changes to increase of control energy induced by operation of PvP.

The subsequent step will therefore comprise the optimisation process. The principle is that the data already evaluated by difference of PvP capacities (the difference between the maximum and the minimum extremes of PvP, see Section 3.) has been plotted in hourly histogram. The bar with the highest value for particular month represents the greatest difference and the highest stochastic nature of PvP possible. The highest bar at specific hour therefore represents the worst impact on control energy during the day and it corresponds with the value of control energy determines by the difference between the initial and final stage of regulatory energy for the particular month. The demand for regulatory energy during other hours is distributed proportionally, as shown in the bar chart with PvP capacity.

The outcome from this optimisation process is the specific known value of regulatory energy, both positive and negative for each hour throughout the day of the particular month. These values have been summarised in Tab. 3, where the value before slash corresponds with MZ15+ and the value behind slash refers to MZ15-.

5. Conclusion

This survey determines the impact produced by integration of PvP into the power grid of the Czech Republic. It is specifically focused on stochastic evaluation of production delivered by these resources leading to interference with the balance between production and consumption of electric power. There has been a clear proof of relevance to the increase of system deviation amplitude. During their peak production periods, photovoltaic power plants represent approximately 20 % share of the total capacity delivered by all power plants. This situation generates two impacts - technical and economical. The power grid operator must comply with engineering criteria defined by international requirements regarding network parameters in order to ensure stability, reliability and safety of operation. All these aspects then affect the economic issues, since there is a greater need for procurement of reserve power in terms of ancillary services. The extent of its direct impact on increase of costs incurred by purchase of ancillary services is rather speculative and this survey does not deal with such issues at all. The survey emphasizes mainly the said technical issues.

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