Extreme Production Conditions of Photovoltaic Power Plant Operated in Distribution Grid

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Abstract. *Photovoltaic power plants are sources of electrical energy that are very dependent on weather conditions. This paper interests in description of stochastic production of power in photovoltaic power plants and subsequently its impact on the distribution power grid. Stochastic production of power from these sources is considerable and hardly predictable. The aim of this survey is to assess the influence of photovoltaic power plants operation on the daily load diagram with regard to output change difference of active power at the relevant substation. Evaluation is based on real-time synchronous data measuring both on-site photovoltaic power plant operation and on-site electric power line output from the substation. This measurement is used for suggestion of a general calculation methodology for the assessment of the difference of active power at a particular node of the grid under various power changes from the photovoltaic power plant. Statistical methods have been employed to process a methodology in order establish extreme conditions of production power for photovoltaic power plant.*

Keywords

Calculation methodology, photovoltaic power plant, real measurement, statistical methods, stochastic effect.

1. Introduction

Dependence operation of both photovoltaic power and wind power plant is considerable on meteorological conditions [3], [4]. This paper contains a description of the assessment focused on the issues of calculation methodology. Most studies deal with the prediction of power as [6], but the purpose of this methodology is to determine differences in active power induced by operation of photovoltaic power plants (PVP). The survey is based on actual long-term monitoring of a specific power plant. The data available has been obtained by measurement at the PVP operation site as well as the point of electric power output from substation plant, where the PVP is connected. Both measurements were conducted on synchronised basis.

The evaluation of PVP production is conducted by means of several individual tasks that can be split into two stages. The first stage determines methodology for set-up of extreme thresholds for production generated by the PVP and the second stage concerns analysis of the impact of these extreme threshold values on the magnitude of active power flows at the place of measurement within substation plant. The reached results from the analysis of PVP are use to establish a methodical calculation model to consider the impact of stochastic production of active power in the PVP on the distribution grid at various nominal values of peak power within various time intervals throughout the year.

The operators of such grids consider the stochastic nature of the power supplied undesirable. Such conditions result in higher demand for reserve capacity in terms of Ancillary Services to ensure the required balance between immediate production and consumption of electric power. Potential changes to power flow represent just another negative consequence. That affects the proper functioning of means for grid protection. There are also problems with keeping the required stable operating grid parameters. This calculation model is established with respect to the potential impact on preserving the magnitude of capacity Ancillary Services [5].

2. Area of a Measured Grid

The data was obtained by measurement both at PVP operation and on the relevant power line output of the substation plant, where this PVP is connected [1].

2.1. Database of Measured Data

1) Photovoltaic Power Plant

The peak output of this PVP is 1.1 MWp. The measurement was conducted on the low voltage side on a continuous basis for one year. Accurately that was from 30.6.2010 till 29.6.2011. The data was recorded with time step set at one-minute increments.

2) Output Substation Plant

The measurement at the power line output was conducted on the high voltage end and ran within various time periods from 26.7.2010 till 23.6.2011. Same as for PVP, the measurement was performed at one-minute increments. The measurement process produced many operating values and parameters. This survey deals with the analysis of the active power P over time path t. Percentage evaluation and mutual comparison of data measured on PVP and at the substation point have been illustrated in Fig. 1. Columns in charts represent individual months. The last column shows an average of all months monitored. In total, there are 98 % of the data from PVE and 64 % of the data from the substation, where:

- p - percent availabilily,
- x-axis - individual months,
- su - average sum of individual months.

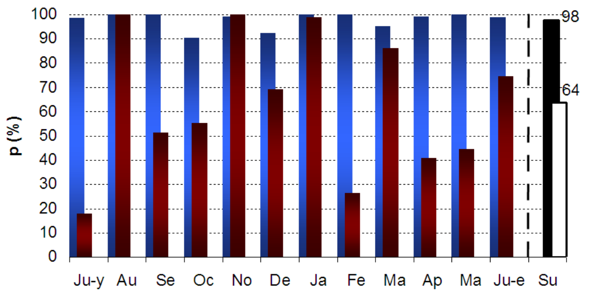


Fig. 1: Percentage comparison of data measured [1].

2.2. Network Topology

The network topology has a loop system, yet it is operated in the radial system. When this measurement was conducted, the PVP was the only electric power source with significant output on a given power line, where:

- PVP - photovoltaic power plant,
- SS - section switch (disconnected),
- 110/22 kV - substation plant 110/22 kV.

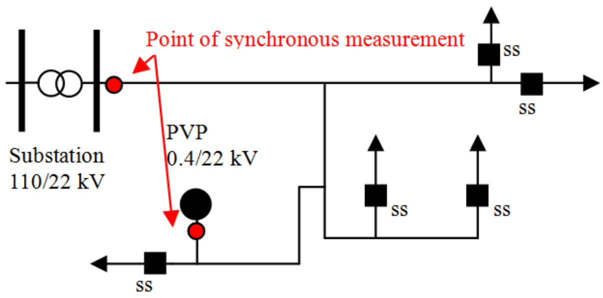


Fig. 2: Measure grid topology [1].

The first measurement was performed at the outgoing feeder from the substation 110/22 kV using the side of lower voltage level of 22 kV. The second measurement was done at the connection point of the photovoltaic plant to the grid at the voltage level of 0.4 kV. Both measurements were conducted in a synchronous manner. Points of measurement are flagged red in Fig. 2.

3. Ancillary Services

The Transmission Grid Code (GC), part II, as amended by revision 14 duly approved by the Energy Regulatory Office on 1.1.2014 in Czech Republic, defines the matters relevant to the utilisation of GC with respect to Ancillary Services. The document contains methodology for determination of summary control backups of SS for the power grid in Czech Republic. One of the prerequisites for determination of summary control backups of SS is the so-called deviation $OD_{OZE(t)}$. This is a parameter to establish the increment of balancing deviation caused by production from newly installed renewable resources of electric power. As stated here (1), this increment is defined by the sum of the increase generated by operation of wind $OD_{VtE(t)}$ and photovoltaic $OD_{FVE(t)}$ power plants. The deviation $OD_{OZE(t)}$ is then used to determine volumes of SS required for the subsequent period, based on existing information from preparations for the operation, e.g.:

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

This statement, described equation (1), implies that the effect of installed capacity of photovoltaic power plants has a certain impact on the calculation of SS. Aim of this survey is to assess if and how much the PVP production has influence to total calculation of SS with respect to individual months. The similar approach of evaluation is also described in [7].

4. Extreme Conditions

The consistency and comprehensibility of this article are supported by the results from own survey to define a methodology for determination of extreme production conditions of photovoltaic power plant. These matters were presented in detail at the conference [2]. Essential results will be described.

4.1. Photovoltaic Power Plant

Figure 3 shows three curves as a sample of analyzed data in this paper. Individual curves correspond as follows:

- producend power from PVP (green),
- power flowing through the substation (blue),
- loads (black).

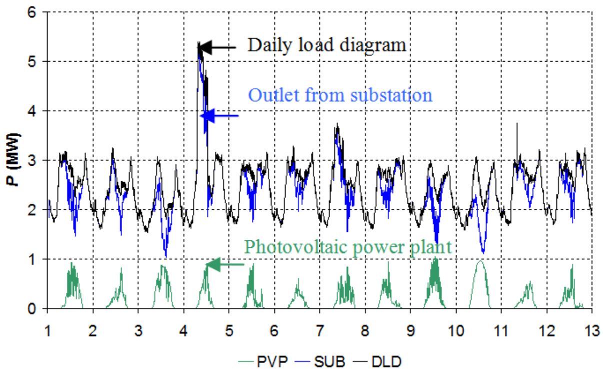


Fig. 3: Sample of examined data.

The power difference of PVP has a negative impact on immediate power balance between production and consumption within the power grid. For this reason, the analysis of extreme thresholds is necessary. Based on factors described in [2], one-minute output series was converted into five-minute increments. Deformation of the data information with respect to further processing and evaluation target is negligible. As an example, further steps described in this article analyse data in April 2011.

Figure 4 shows extreme areas of PVP production (the green curve from Fig. 3. The thresholds of these extreme conditions are defined by two regression polynomial Eq. (2) and Eq. (3), which form the top and bottom envelope curves of stochastic changes in the produced power. The equations are as follows:

$$\begin{aligned} P_{FVEmax} &= -5700,51 + 63525,7 \cdot Time \\ &-246642 \cdot Time^2 + 400745 \cdot Time^3 \\ &-279206 \cdot Time^4 + 66861,7 \cdot Time^5, \end{aligned} \tag{2}$$

$$\begin{aligned} P_{FVEmin} &= 4554,05 - 68932,4 \cdot Time \\ &+414328 \cdot Time^2 - 1,25591 \cdot 10^6 \cdot Time^3 \\ &+2,0145 \cdot 10^6 \cdot Time^4 - 1,62904 \cdot 10^6 \cdot Time^5 \\ &+523013 \cdot Time^6. \end{aligned} \tag{3}$$

Determination of these extreme conditions was conducted based on statistical methods that utilize the relevant frequency categories using the so-called Sturges rule. This is a rule for optimal determination of frequency categories. Next step is to evaluate daily load

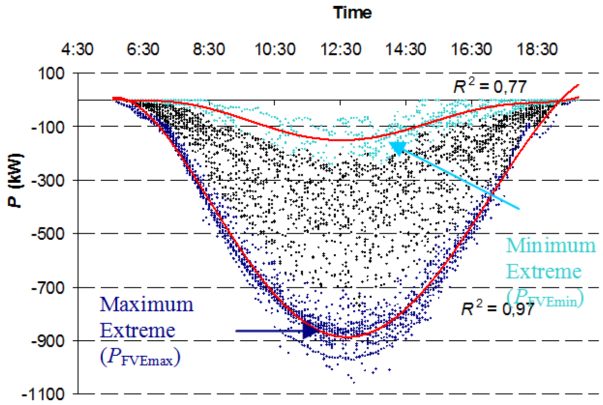


Fig. 4: Extreme conditions of PVP.

diagram. Correlation fields of daily load diagram (the black curve from Fig. 3) can be subject to regression analysis applied to enable determination of differential power thresholds of loads. It is described in Fig. 5. Extreme threshold conditions, Eq. (4) and Eq. (5), have been determined using 95 % prediction levels. For more information on this issue refer to [2]. The equations are as follows:

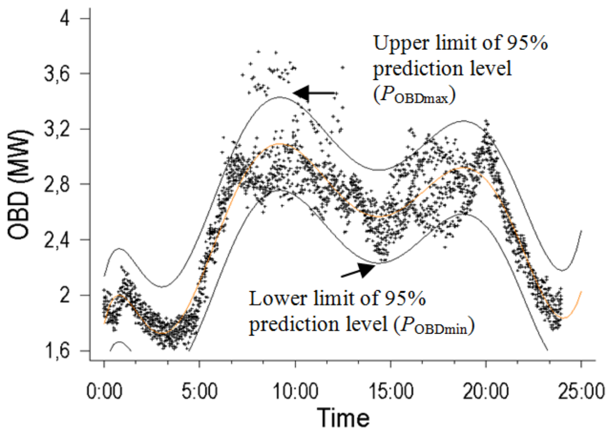


Fig. 5: Extreme conditions of daily diagram.

Previous analyses have produced the extreme difference of output generated by PVP and determination of thresholds for daily load diagram. Extreme conditions that might occur at the substation plant outlet correspond with the sum of extreme conditions both PVP

$$\begin{aligned} P_{OBDmax}(MW) = 2,13445 + 0,000174187 \cdot Time - 4,6908 \cdot 10^{-8} \cdot Time^2 + 4,32657 \cdot 10^{-12} \cdot Time^3 \\ -1,78877 \cdot 10^{-16} \cdot Time^4 + 3,85326 \cdot 10^{-21} \cdot Time^5 - 4,49778 \cdot 10^{-26} \cdot Time^6 \\ +2,69318 \cdot 10^{-31} \cdot Time^7 - 6,46948 \cdot 10^{-37} \cdot Time^8, \end{aligned} \tag{4}$$

$$\begin{aligned} P_{OBDmin}(MW) = 1,45615 + 0.000176551 \cdot Time - 4,72509 \cdot 10^{-8} \cdot Time^2 + 4,35116 \cdot 10^{-12} \cdot Time^3 \\ -1,79852 \cdot 10^{-16} \cdot Time^4 + 3,87564 \cdot 10^{-21} \cdot Time^5 - 4,52732 \cdot 10^{-26} \cdot Time^6 \\ +2,71398 \cdot 10^{-31} \cdot Time^7 - 6,52996 \cdot 10^{-37} \cdot Time^8. \end{aligned} \tag{5}$$

and the daily load diagram. They have been defined as follows:

1) Maximum Extreme Conditions:

matching the maximum extreme condition that may occur. It is equal to the difference between the maximum extreme of DLD (upper prediction level 95 %) and the minimum extreme of PVP:

$$P_{ROZ(max)} = P_{OBD(max)} - P_{FVE(min)} \ (MW). \tag{6}$$

2) Minimum Extreme Conditions:

matching the minimum extreme conditions that may occur. It is equal to the difference between the minimum extreme of DLD (lower prediction level 95 %) and the maximum extreme of PVP:

$$P_{ROZ(min)} = P_{OBD(min)} - P_{FVE(max)} \ (MW). \tag{7}$$

These curves Eq. (6) and Eq. (7) are portrayed in Fig. 6. They demonstrate the maximum extreme conditions that may occur for a relevant outlet of the grid at the outgoing feeder from the substation. In order to control of developed methodology, the measured data of flowing power at the point of the substation (the blue curve from Fig. 3) are plotted in calculated competent thresholds of curves describing the minimum and maximum extreme power (described in Fig. 5) which could occur at the outlet from the substation plant. This situation shows Fig. 7. All the data and evaluation methodology were considered with the reliability level of 95 %. This particular case concerns 95.54 % of values situated within the defined output extreme conditions. This fact justifies the correctness of the process.

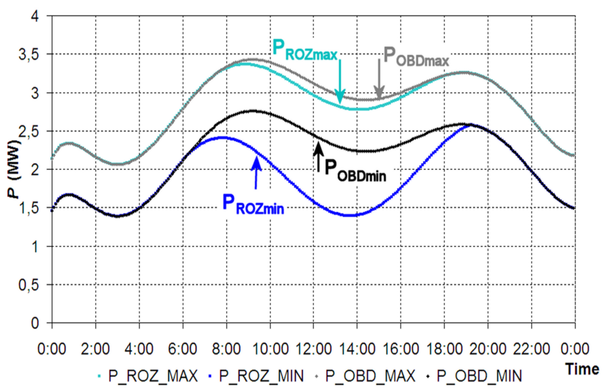


Fig. 6: Substation outlet extreme conditions.

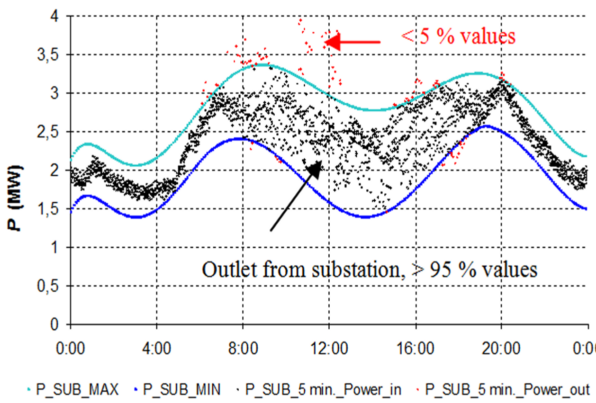


Fig. 7: Control of adjustment of power output difference tresholds.

5. Suggested Methodical Models

5.1. Assessment Methodology

The process of assessment methodology is described by the block diagram in Fig. 8. The diagram is divided into three vertical and three horizontal sections. Vertical columns are separated by a dashed vector, and horizontal lines are highlighted by blue background.

1) Vertical Sections

The first column represents measured data fundamental for the establishment of this methodology.

The second column provides a description of suggested calculation methodology. The first step required processing of data, or the so-called Post-Processing (block P.-Process.). The next step was to enumerate extreme conditions for power output of photovoltaic power plants (block Extr. PVP), extreme conditions of the daily load diagram (Extr. DLD) and extreme conditions at the outgoing feeder from the substation (Extr. SUB). Determination of Extr. SUB firstly required obtaining the data without impact of production from the PVP. This data represents so-called the row data (only loads) for daily load diagram (block DLD). The row data was determined by subtraction of the immediate output data during operation of PVP from the immediate output data measured at the substation. This subtraction is subject to accurate synchronising (block Synch.) of both sets of data measured. Subsequently, extreme conditions of DLD were evaluated. Suitable sum of Extr. DLD and Extr. PVP can help with assessment of extreme conditions occurring at the substation (block SUM Extr.).

The last column contains differences of active power of the PVP (block P diff. PvP) and the data measured at outgoing feeder from the substation (block P diff. SUB and P diff. DLD).

2) Horizontal Sections

As previously mentioned, the diagram is also divided into three horizontal lines.

The first line comprises blocks linked by means of red arrows. These describe the steps for assessment of power differences on the PVP itself only. This indicator does not include the impact of daily load diagram. This assessment is then used to determine the model situations for individual months with further potential for flexible alterations according to the panel type already known and its nominal peak power. This step is the most important and difficult of all evaluation.

The last horizontal line contains blocks linked with green arrows. The data measured at substation includes the impact of PVP operation too. Determination of the difference of active power in this manner is correct, although dedicated only. It cannot be applied to another model situation in a broader sense, being limited to these specific data measured at this particular substation and the relevant PVP.

These issues do not also deal with a case, when the difference of active power would change with the construction of a new PVP within the particular location.

The second line proves itself as an optimal solution, and it is linked to blocks using blue arrows. We need to realize that extreme conditions of power at the substation occur due to extreme conditions on both the PVP as well as a daily load diagram. As mentioned previously, the data measured at outgoing feeder from the substation must be reduced by subtracting the data pertaining to power produced by the PVP. This stage already enables to determine the extreme conditions of daily load diagram as well as PVP for any types of panels with varying peak power figures.

Model situations of extreme conditions of PVP may also be useful for various model or simulation processes, where the change to load diagram is already anticipated.

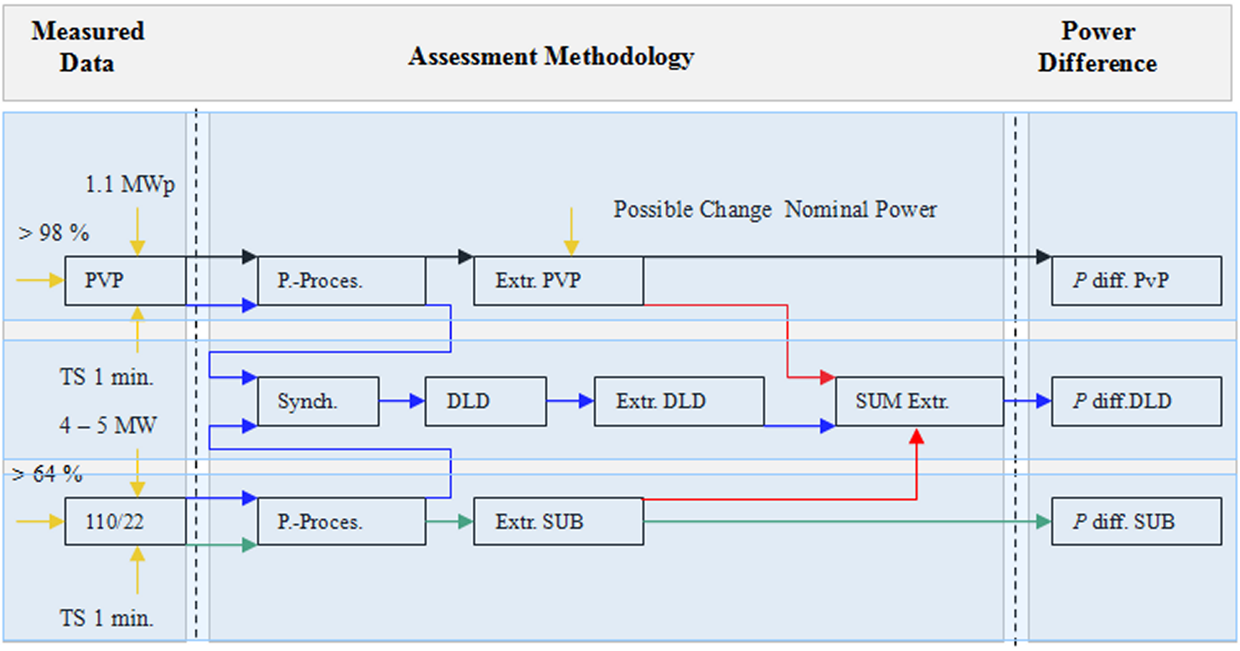
5.2. Calculation Model

The suggested assessment methodology can be used to set up a calculation model. The calculation model contains blocks linked with red arrows.

The main advantage of the very assessment of extreme states to PVP and DLD has been described above. This idea has been also transferred into the calculation model. Another irrefutable advantage brought by analysis of such separated data is a more accurate mathematical description. It has to be realized that the DLD and PVP production curves differ greatly in nature that is also one of the reasons, why examining either extreme separately is more convenient before calculation of model situation of extreme conditions of PVP (block PVP) requires knowledge of the panel type and their nominal peak power figures. Further requirements to be met include the precondition assuming static position of the panel in order to maximize profit (inclination at approx. 38° with respect to the horizontal plane and southwards orientation). The red arrow in Fig. 8 represents the integration of model extreme conditions of PVP into the calculation process and the point of assessment. The point for assessment (block 110/22), which is to be used for assessment of the power difference, must be identified with the nature of power load - the daily load diagram. These load curves are usually monitored by distributors at certain vital points. Data originating from various model or simulation processes can be also used.

5.3. Annual Extreme Conditions of PVP

Maximum extreme conditions of production are described in Fig. 9 and Fig. 10. Figure 9 covers months within the period from December till June, i.e. the periods of winter and summer solstice. One can no-



PVP – photovoltaic power plant,
110/22 – substation 110/22 kV,
P. - Process. – post-processing of data file,
Synch. – synchronising of measured data,
DLD – data of the daily load diagram,
Extr. PVP – extreme conditions of PVP,
Extr. DLD – extreme conditions of the daily load diag.,
Extr. SUB – extreme conditions at the substation 110/22 kV,
SUM Extr. – resultant extreme conditions,
P diff. PVP – active power difference of Extr. PVP,
P diff. DLD – active power difference of Extr. SUB, with inclusion of model Extr. PVP,
P diff. SUB – active power difference of Extr. SUB, without inclusion of model Extr. PV.

Fig. 8: Block diagram of assessment methodology.

tice 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. This case therefore leads to the establishment of an optimal ratio between the intensity of solar radiation and average temperature during the particular month (previous months indicate lack of solar radiation and the subsequent months bring higher ambient temperature with a negative impact on panel efficiency). Figure 10 shows maximum curves from July till December, i.e. between the summer and winter solstice.

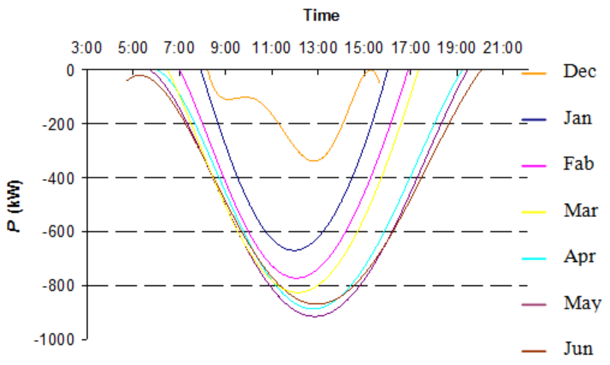


Fig. 9: Extreme conditions of PVP, December to June.

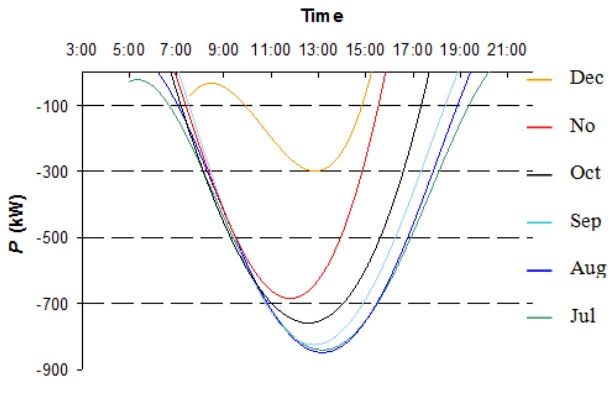


Fig. 10: Extreme conditions of PVP, July to December.

6. Conclusion

Briefly speaking, this measurement is used for suggestion of a general calculation methodology for assessment of difference o active power at a particular node of the grid under various fictional changes to power from the photovoltaic power plant or the whole solar farm, or even in case of expected changes or predictions in the daily load diagram. Comparing maximum extremes of each month indicates significant differences. It is clear that different periods during the year have influence to the assessment of Ancillary Services. Next Steps of this study will focus on the application of this methodology on a full database and evaluation the relationship of each month to Ancillary Services.

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