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Methodology for Extreme power thresholds of photovoltaic power plants

Abstract. *Photovoltaic power plants are significant for their dependence on weather conditions. The consequences include their stochastic change to the production power that has adverse impact on electric power distribution grids. The aim of this survey is to assess the impact of photovoltaic power plants operation on the daily load diagram with respect to output change difference of active power. Statistical methods have been employed to process a methodology based on real-time data measuring both on-site photovoltaic power plant operation and on-site electric power line output from the substation, where the power plant is connected. Both data are measured by synchronous means.*

Streszczenie. *Celem artykułu jest ocena wpływu pracy system fotowoltaicznego na dzienny rozsył energii z uwzględnieniem zmian mocy czynnej. Mierzono w trybie on-line warunki operacji elektrowni fotowoltaicznej i pobór mocy z linii. (**Metodologia oceny wartości progowych systemu fotowoltaicznego**)*

Keywords: photovoltaic power plant, extreme production conditions, power differences, methodology
Słowa kluczowe: elektrownia fotowoltaiczna, rozsył energii

Introduction

This paper deals with stochastic analysis and assessment of database comprising data obtained by measurement on a photovoltaic power plant (PVP). The results obtained will be used for calculation methodology to be used for determination of model to be implemented for assessment of power change difference.

The model and methodology for assessment have been based on real time measurement of value on a specific PVP and the relevant electric line output from substation.

The data was processed and evaluated using the Excel Microsoft Office 2003 chart processor and Statgraphic XV statistical software pursuant on the theory of statistics.

Measured data

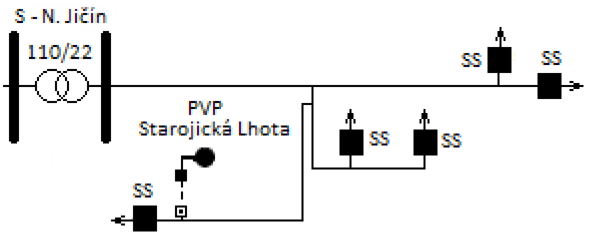
The data was obtained by measurement at PVP in the municipality of Starojická Lhota and on power line output (vn51) of the substation in Nový Jičín, where this PVP is connected [2].

PVP, Starojická Lhota:

The peak output of this PVP is 1.1 MWp. The data was obtained on the low voltage (NN) end. The measurement was conducted on continuous basis for one year; that was from 30.6.2010 till 29.6.2011.

Substation, Nový Jičín:

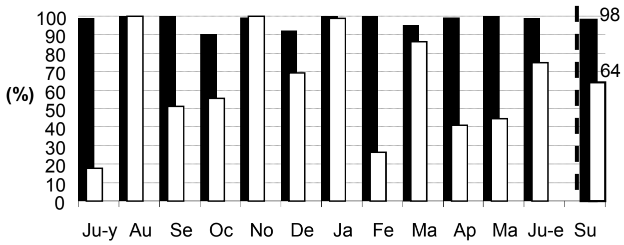
The data was obtained at the substation in Nový Jičín, specifically the power line marked vn51. This measurement was conducted on the high voltage (VN) end. The line has a loop system, yet it is operated in radial system. The measurement ran within various time periods from 26.7.2010 till 23.6.2011. Fig. 1 shows graphic illustration of a simplified network topology.



SS – section switch (disconnected), S – substation

Fig. 1 Network topology in analysed area

Percentage evaluation and mutual comparison of data measured on PVP and at the substation point have been illustrated in Fig. 2. Columns in charts represent individual months. The last column shows an average of all months monitored.



PVP – black columns, vn51 – white columns

Fig. 2 Percentage comparison of data measured

Thresholds of PVP

Production of electric power by means of PVP is predisposed by the course of 24-hour daily cycle. The cycle describes a curve of Gauss distribution with maximum values in the afternoon and minimum during morning and evening hours respectively [1]. Such distribution of electric power production is undesirable, when compared to the daily load diagram. One could basically conclude that the curve representing production of electric power from PVP shows negative correlation to the daily load diagram curve. The share of PVP on covering morning and evening peaks during morning and evening hours is very slender. The peak output of this power plant is reached during afternoon hours. Due to its dependency on direct sunlight, there are many occurrences of short-period peaks. These peaks do not correspond with the daily load diagram.

Post processing

Post processing of data files can be divided into the following three stages:

- filtering and correction of data,
- data analysis,
- final evaluation arrangements.

The article further deals with correction and evaluation of data obtained by measurement at PVP Starojická Lhota for April 2011 only.

Data File Correction

Five-Minute Output Series:

Data records were made every minute. As far as the network endurance to short-term dynamic changes is concerned, evaluation of one-minute output series is undesirable, whereas the time frame should be higher with respect to this characteristic network [4]. Further reasons include the problematic synchronisation of data between databases of the PVP and the vn51 line from the substation respectively. The above mentioned factors (network endurance and data synchronisation) resulted in conversion of one-minute output series into five-minute increments. Deformation of the data information with respect to further processing and evaluation target is negligible. The data file for April 2011 comprises 8,568 entries.

Night Time Operation:

Every data file contains records from night time, when the power plant is not producing any output and even draws certain amount of electric power. With respect to further evaluation, this data is filtered out of the data file, as it might affect the statistical evaluation significantly. The amount of electric power drawn by PVP is way below the amount of electric produced, so the PVP power consumption can be disregarded. The power plant is therefore considered idle during night time. The data file is reduced further to mere 4,704 entries only.

None of these corrections to the data file or its relevance to the subject matter of evaluation invalidates the fundamental information.

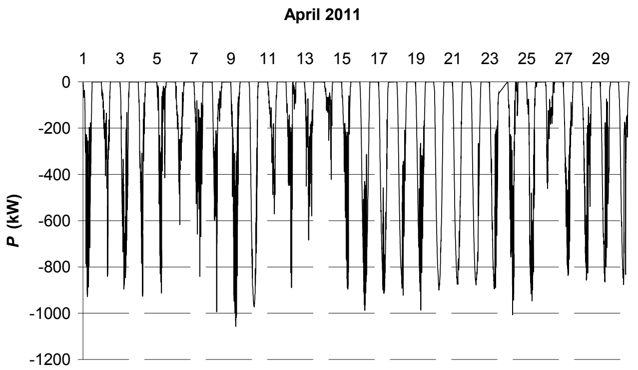


Fig. 3 Course of production output after data filtering

Fig. 3 shows partial illustration of the course of power production during the relevant month observed, including the above mentioned correction and data filtration. Days with adverse and favourable weather conditions can be estimated visually together with extreme conditions of production.

Data Analysis

For extreme production conditions, the PVP can be assessed with respect to two extremes. These relate to the maximum and minimum production output respectively. The minimum production output is experienced during morning and evening hours, while the maximum production occurs during afternoon.

Under extreme conditions, the PVP requires supporting services to ensure loads within the daily load diagram. Another step of data correction must be taken individually with respect to evaluation target (maximum production extreme, minimum production extreme).

Maximum Production Extreme

Fig. 4 shows the correlation field with maximum five-minute output series of production per day. These values shows the most important information for evaluation of such extremes and therefore these cannot be filtered out of the data file under any circumstances. Linear regressions equation provides unambiguous potential approximation by means of constant function with respect to function coefficients. The graphic output material shows evident outlier points. Considering this statement, those extremes cannot be substituted with their mean values (arithmetic average), as the parameter is strongly dependent on outlier points and requires the Gauss normal distribution of probability for small number of values. As far as such case is concerned, the number of outliers and the total number of values can be considered a small proportion of the input file without any statistical testing.

The parameter not directly affected by magnitude of values of a particular variable is called a median. Median provides a good idea of objective position of the middle value implying the level of values associated with the variable observed [1]. Median is not affected by extreme outlier points in any way. The value of median for maximum daily values is equal to 896.43 kW.

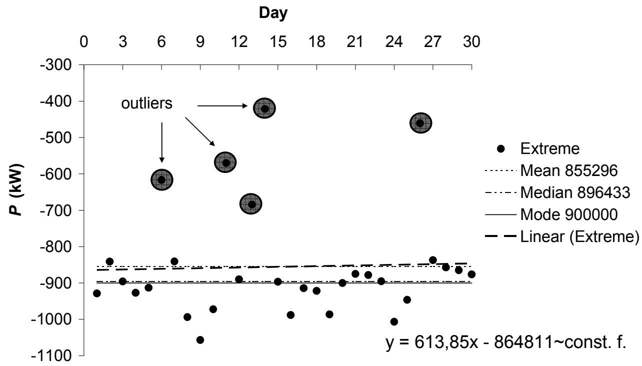


Fig. 4 Maximum power values each day

The point diagram showing output from PVP within the period of analysis is shown in Fig. 5. Further step of evaluation comprises approximation of the scatter plot by means of corresponding regression curve, which will include the extreme values required (condition No. 2 - Fig. 4) in accordance with defined statistical evaluation methods (condition No. 1 – index determination $R^2 > 80$ % [1]).

The regression analysis shown in Fig. 5 does not correspond with defined entry condition. The entry condition No. 2 states the desired preservation of values produced by extreme daily outputs. The median of these extreme outputs does not overlap the extreme of regression analysis curves. The regression curve in Fig. 5 illustrates not only mean values yet also medians of five-minute output series. The coefficient of determination does not meet the requirement $R^2 > 80$ %, i.e. the condition No. 1. Those are factors pointing at the inconvenient nature of this evaluation.

Fig. 5 provides the opportunity to observe that the highest frequency of five-minute output series is projected by the envelope curve; that is in the field of extreme maximum output. This fact represent the basis for further correction of data consisting of division of particular five-minute power series into the relevant frequency arrays using the formula $1+3{,}3\cdot\log(N)$, where N refers to the number of values [1]. It is the so called Sturges rule for optimal determination of frequency categories. Further step comprises selection of category with the highest frequency of values (also the highest value of produced output). It is the category on the border with envelope curve. Such filtered-out data is shown in Fig. 6.

The regression analysis in Fig. 5 does not fulfil any of the conditions defined above. The analysis shown in Fig. 6 shows compliance with both of the above mentioned conditions. The median of extreme daily power almost corresponds with the extreme of power regression curve, complying with condition No. 1. The index of determination R^2 > 80 % validates strong regression and therefore meets condition No. 2 (the model explains the great dispersion of values [1]).

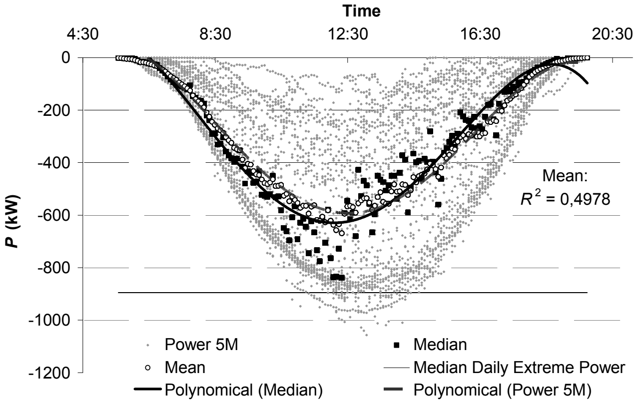


Fig. 5 Point diagram of output

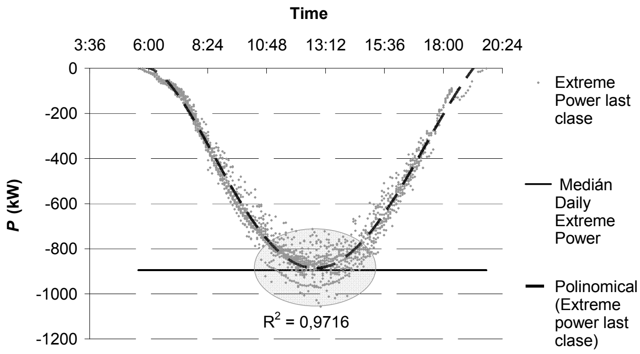


Fig. 6 Power frequency category bordering with the envelope curve

The result of this methodology for evaluation of maximum extreme conditions of PVP is represented by the polynomial equation of 5th grade to approximate these maximum values. The equation has been calculated using the Statgraphic software in the form shown below:

$$(1)\quad P\,(\mathrm{W}) = -5700510 + 63525700 \cdot Time - 246642000 \cdot Time^2 + 400745000 \cdot Time^3 - 279206000 \cdot Time^4 + 66861700 \cdot Time^5$$

where: *P* – active power (W), *Time* – time (00:00:00).

Minimum Production Extreme

Evaluation of minimum extreme conditions is based on similar methodology as determination of maximum extreme conditions.

The initial idea was to use graphic illustration of the produced output to define the interface between direct solar radiation and diffusion radiation respectively. As the visual assessment of graphic illustration showed evident certain proportion of the diffusion element, the objective determination of their overall share was very difficult. It shall be realized that even during clear sunny days applies to both direct and diffuse radiation element. The measurement process should be ideally supplemented with records focused on shares attributable to direct sunlight and diffusion radiation. The only option to establish the approximate share of diffusion radiation is to calculate it in terms of amount of electric power produced and the known rough ratio of the direct sunlight and diffusion radiation during particular months. The ratio between direct and diffusion radiation elements can be obtained from sources dealing with such matters, one of the examples would be [3].

Approximation of minimum extreme conditions in production by means of a constant function equal to zero would not be a convenient solution either, as the graphic illustration does not show certain diffusion radiation element clearly (see Fig. 7).

So, another step was to determine this threshold in a different way in order to respect the diffusion radiation element that is 100% identifiable by visual assessment in accordance with Fig. 7. It is basically the minimum threshold of guaranteed share of diffusion radiation element. This information provides far better informative value about the minimum production at PVP compared to the above mentioned overall diffusion radiation element. Other surveys clearly show that the element will adopt difference share sizes in various seasons [3].

Fig. 7 shows a scatter plot of one-minute power series over one month of monitoring. The occurrence of guaranteed diffusion radiation is evident. It is located in the area missing any power values.

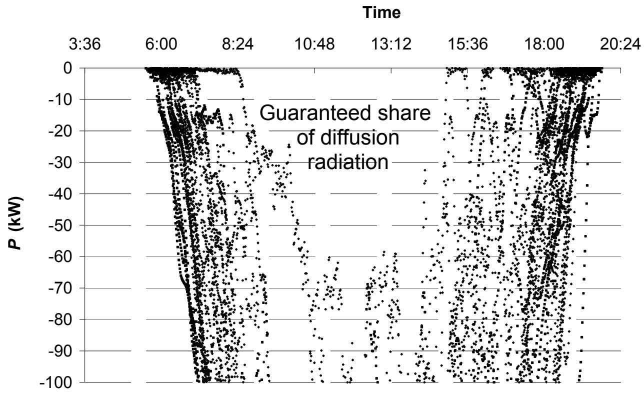


Fig. 7 Guaranteed share of diffusion radiation

It is therefore necessary to determine conditions. The condition No. 1 implies respect to the impact of minimum guaranteed diffusion radiation. The condition No. 2 is the same as for maximum extreme conditions of production; that means conformance of evaluation with statistical methods, i.e. R^2 > 80 %.

At this stage, it is desired to define the clear threshold for minimum production of PVP; and that will be independent of the significance of diffusion radiation share. Correction of data consists of classification of particular five-minute output series into relevant frequency categories using the formula 1+3,3·log(*N*). Further step deals with selection of category with the lowest power production value. It is the category on the border with envelope curve. Such corrected data is shown in Fig. 8.

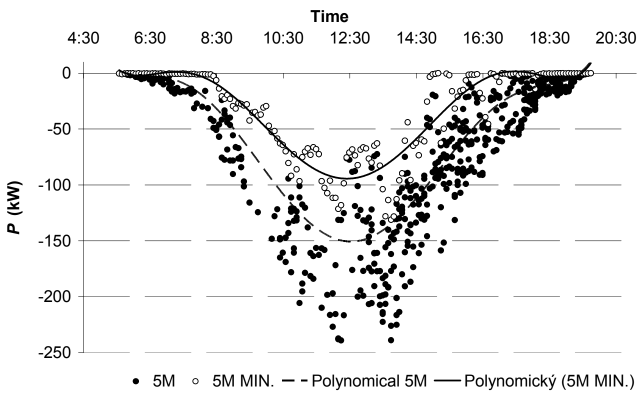


Fig. 8 Five-minute power series in the minimum production field

This matter was subject to two regression analyses. The first regression includes five-minute power series in category one (the lowest production values) distribution of data frequencies (dashed curve) and the second one represents the minimum five-minute output series of guaranteed diffusion radiation for certain time in the observed period (solid curve). More detailed analysis was employed to select the first regression.

The index of determination $R^2 = 77$ % does not correspond with the set $R^2 > 80$ %, which would define the required dependency between the power dispersion and time. Fulfilment of these conditions is not as strict for as for evaluation of maximum extreme conditions. The important thing is that the dispersion of power values experienced here is not as large as for maximum extremes. The optimal settings of R^2 for evaluation of minimum extreme conditions will be subject to further survey. The index of determination $R^2 = 77$ % is sufficient in this case and the validity of regression is fully justified. The condition No. 2 has been met. The condition No. 1 has been also met automatically, as 77 % of the variable to be explained has been clarified by means of model - the model explains the minimum values of power from guaranteed diffusion radiation (extreme of curve - Fig. 8) and inaction production in the early morning and evening hours too (curve passing through zero power – Fig. 8).

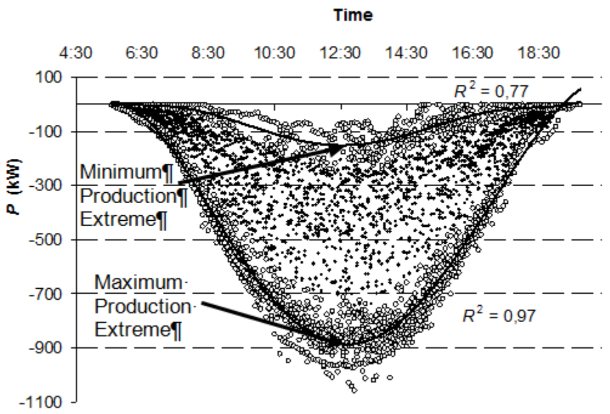


Fig. 9 Regression of both extreme production conditions

The result of this methodology for evaluation of minimum extreme conditions of PVP is represented by the polynomial equation of 6th grade to approximate these minimum values. Polynomials of lower grade did not pass through the zero on *y* axis, which was contradictory to the actual condition. The equation has been calculated using the Statgraphic software in the form shown below:

$$P\,(\text{kW}) = 4554{,}05 - 68932{,}4 \cdot Time + 414328 \cdot Time^2 - 1{,}25591 \cdot 10^6 \cdot Time^3 + 2{,}0145 \cdot 10^6 \cdot Time^4 - 1{,}62904 \cdot 10^6 \cdot Time^5 + 523013 \cdot Time^6 \quad (2)$$

where: *P* – active power (W), *Time* – time (00:00:00).

Fig. 9 illustrates envelope regressions curve for both extreme production conditions of PVP.

Conclusion

This part of the survey describes a new methodology for statistical evaluation of database containing data measured on a photovoltaic power plant. The matter involves determination of extreme conditions in production. The result comprises two polynomial equations to represent these extremes.

There is a similar procedure of statistical evaluation being currently applied to the daily load diagram showing the load in location of specific PVP. The already evaluated minimum and maximum extremes of PVP production are further compared to the said daily load diagram. The whole evaluation methodology will be further applied to the entire database of data measured.

Acknowledgments

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