Dynamic changes of photovoltaic power plants power supply

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Abstract — **The aim of this work is to analyse the dynamics of the power production curve of Photovoltaic Power Plant (PVPP). The paper is focused on selected results of experimental activities related to photovoltaic production. Moreover, the theoretical background of inclusion of PVPP to the daily load diagram of a Slovak TSO (transmission system operator) is discussed. In the theoretical part, technical and environmental effects of the PVPP dynamic power production and corresponding mathematics and statistics is listed. Dynamic changes in PVPP production are statistically compared utilising data taken from selected PVPPs various technology and installed power. Dynamic changes of the PVPP power production can be used to optimise the analysed power system. These results are important to properly set regulation system settings of other Smart Grids. Technical solutions of virtual power plants, power regulation and others are verified and correlated with experimental data of Smart Grid systems involving PVPP.**

Keywords: power output, dynamical changes of power output, photovoltaic power plant, Smart Grid, power regulation

I. Introduction

Electricity production is bound to be the primary energy source. For electricity production humankind primarily uses thermal power plants which burn fossil fuels (72.9% of electricity production in the world [1]). The maximal efficiency of thermal power plants (efficiency of transformation of primary energy source to electricity) is about 41.6% [2]. It means that nearly 60% of the energy of primary fossil fuels is not used and it is wasted by nature in these power plants.

Renewable energy sources (RES) produce electricity constrained by natural conditions. They produce electricity from sources which are constantly renewing naturally or by human activity. In this way; these sources are inexhaustible.

RES are at the moment not capable of replacing all fossil power plants. There are two primary reasons: The first one is because most RES power plants have no storage of primary energy sources. They produce electricity only under suitable conditions. This makes them hardly adaptable to the power load of the electric system. The second reason why they cannot replace traditional power plants so easily is that the technology of these systems is more expensive. The production level of RES systems is increasing, because of response to investors' demand. By increasing the demand in the market, the price of these technologies should decrease. The increase in electricity price has a positive effect on RES due to better and sooner return on investment. The operation of these sources should not be affected by fluctuation of primary sources (fossil fuels) price, too [3].

Not counting hydro power, the most prevalent RES in Slovakia is power produced from biomass and biogas. Photovoltaic power plants (PVPPs) are only the third largest renewable electricity source [4]. Power plants which produce electricity from biomass and biogas have continuous production curves and they do not affect system energy imbalance. In contrast, PVPPs are highly dependent on weather conditions and their supplied power changes sharply. It depends not only on weather conditions, but on power electronics, too.

Because of early economic payback, the operator of residential PVPP is trying to exploit the power from PVPP in the place of production. This mean, operator is trying to adapt its own consumption to PVPP production [5]. If this adaptation to consumption is intelligently managed and it is automatized, then we are moving to the vision of Smart Grids. Definition of Smart Grids is different in different literature, but we have to deliberate, that these systems must be a superstructure of existing systems. We have to adjust measurement and control of these existing systems [6].

If we want to merge control of different devices in Smart Grid systems, we should recognize these individual devices. For this reason, we are focusing on the dynamics of power production from PVPPs.

II. OPERATING OF RES

Operator of PVPP is trying to produce as much power as possible from PVPPs, because the reward stands for produced MWh. However, power producers are by law not permitted to trade the produced energy and they are usually not responsible for the power plant energy imbalance. The repurchaser (energy supplier/trader) is responsible for the PVPP (or other RES power plant) energy imbalance and is trading the produced energy.

Impact of RES to the power system can be divided into two major categories: local impacts and impact to the whole power system. Impact to voltage, short circuit power, supply of harmonics current, impact to mass remote control, flicker and others are local impacts. Operator of distribution system have to follow the rules of electricity quality, which is described in norm *STN EN 50 160 Voltage characteristics of electricity supplied by public electricity networks.* The distribution system operator issues document *Technical conditions of the distribution system operator (valid from 01-05-2019)* for this reason. In this document, all technical requirements and standards to connect new power sources are mentioned

Impact to system stability, insertion of RES power production to daily load diagram and energy imbalance caused by RES are impacting the whole system. Overload of transmission lines caused by RES is another issue, which is closely related to RES development in the power system. This overloading can cause non-compliance of criterion N-1 of the power system [7].

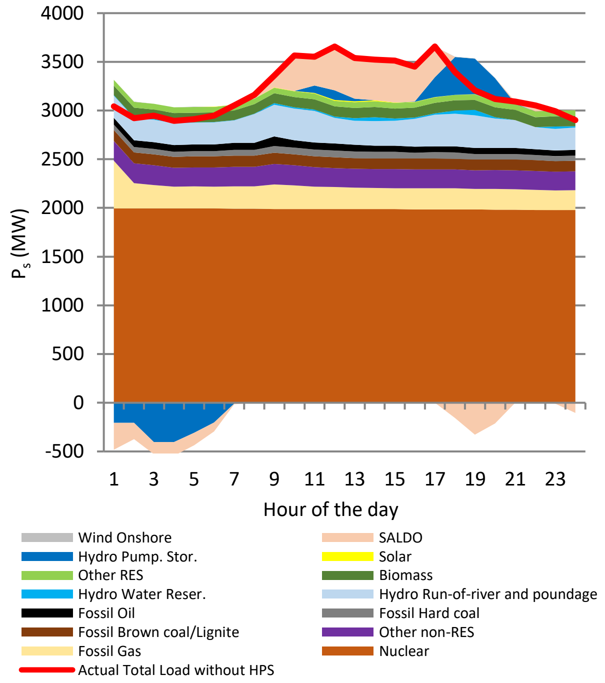

Figure 1. Daily diagram of system load at day with minimal production of PVPP (24.12.2021)[8]

Figs. 1 and 2 show which part of electricity consumption is covered by RES (especially PVPPs) during the day with maximal production of PVPPs and during the day with minimal production of PVPPs.

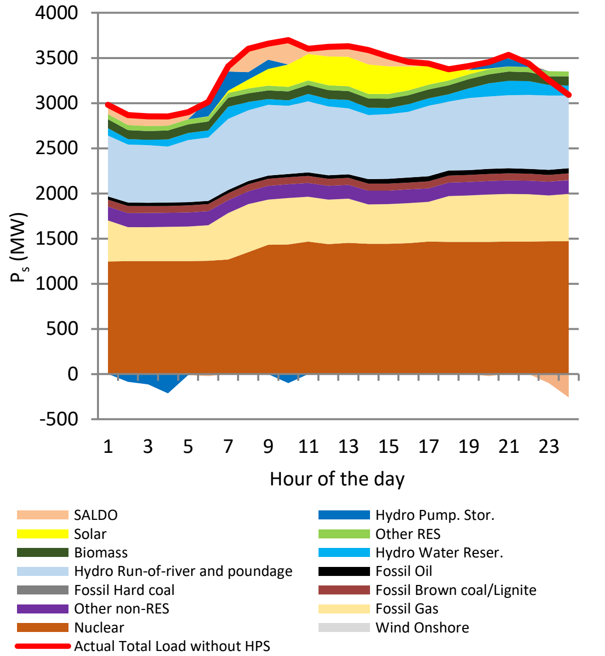

Figure 2. Daily diagram of system load at day with minimal production of PVPP (26.05.2021)[8]

Rentability of investments to RES were not profitable in the past. Therefore, electricity produced by RES was subsidised. Some subsidies are still active. Electricity market is run by 1 hour intervals, but energy imbalance is evaluated in 15 min intervals. This results in a higher cost of energy imbalance for a purchaser of this electricity as even very precise hourly predictions cannot eliminate energy imbalance in 15 min time intervals.

III. THEORY

Modern inverters and DC-DC converters for PV systems use MPPT (maximum power point tracker) technology. This technology consists of an electronic circuit, which adapts input voltage from photovoltaic panels. This circuit looks for an optimal operating point at the VA curve in order to gain maximum power (P_m.) This power in W is determined as follows:

$$P_{mp} = U_{mp} I_{mp} \qquad [W] \tag{1}$$

where U_{mp} is the voltage in V and I_{mp} is the current in A at maximum power P_{mp}. The current at each point of the VA characteristic can be determined from the following equation:

$$I = I_L - I_0 \left[exp \frac{e(U+IR_S)}{mkT} - 1 \right] - \frac{U+IR_S}{R_P} \qquad [A] \tag{2}$$

where I_0 is the saturation current in A of PN junction dependent from temperature, e is the electron chargein C, U is the belonging voltage in V on VA characteristic, m is the ideality factor (-) of the semiconductor element, k expresses Boltzmann's constant in $m^2kgs^{-2}K^{-1}$, T is the actual temperature in K of PN junction and R_s with R_p are parasitic resistances (serial and parallel) in Ω, which depend on type of solar cell.

These resistances are nonlinear elements and they vary on temperature. The current I_L is produced by light in A:

$$I_L = eA_c \int_{E_G}^{\infty} S(E)\eta_{qe}(E)dE \quad [A] \tag{3}$$

where *S(E)* is the number of photons with energy *E* ($cm^{-2}s^{-1}$), affecting PN junction with external quantum efficiency η_{qe} (-) on the area of A_c in cm^2. Integral is limited from the bottom by the energy of E_G in J, which is the wildness of the forbidden zone of semiconductor.

From the equations (2) and (3) one can see that the magnitude of the current and the magnitude of the power from each cell of the photovoltaic panel depends on solar irradiation intensity and temperature Other parameters are constants or they depend on used material of photovoltaic cells and their structure [9].

The curve of power delivered to the network is also affected by the efficiency of the power inverter. These losses are produced by current conversion (DC to AC) and they increase with the square of current. The supplied power is even reduced by the inverter's own power consumption, while not depending on supplied power. It can be various under different operating states of the inverter (daytime operation, nightly operating, disconnected PV, disconnected grid and combinations of these operating states).

In the datasheet of the inverter of PVPP no. 1, just two distinct values are stated: the maximum efficiency of the inverter, which is 98%, and the night consumption of 0.5 W. In the datasheet of inverters used for PVPP no.2, the dependence of efficiency on output power (P_{AC}) is shown in detail (Fig. 3).

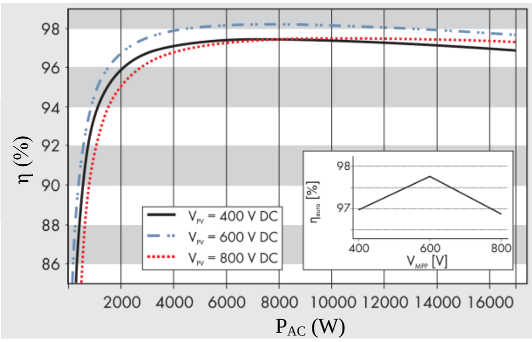

Figure 3. Efficiency dependence on produced power of inverters used for PVPP no. 2

Both types of inverters (Table 1.) have an installed power of 17 kW and the efficiency is higher than 98% for output power higher than 12% of the installed power (2000 W). Errors caused by non equivalency of 2 types of inverters are negligible for the analysis below.

IV. Dynamical curve of produced power by PV

Power production of PVPP is possible to be predicted in 15 minutes or hour intervals using meteorological data. But the supplied power of PVPP changes more rapidly (every second, or even less) due to the changes in solar behaviour. Rate of this power change depends on the current produced by the PV cell and also on the reaction time of MPPT of the inverter (frequency of maximum power point evaluation). Measured data in this work are produced by photovoltaic power plants at the Institute of materials and machine mechanics of Slovak Academy of Sciences. The data acquisition rate here is in second resolution.

We will consider the relative percentage performance *p* for clarity in %:

$$p = \frac{P_t}{P_{inst}} \cdot 100 \quad [\%] \tag{4}$$

where P_t in W is supplied power in the time period of *t* in seconds and P_{inst} is the installed power of PVPP in W. Similarly, the second power change (related to installed power) will be considered as follows:

$$\Delta p_t = \frac{P_t - P_{t-1}}{P_{inst}} \cdot 100 \quad [\%] \tag{5}$$

It means that positive change will increase power and negative change will mean power reduction. Two indicators of dynamic changes will be used. The first one is the average of absolute values of power changes per second Δp_{Φ} (related to installed power) in %:

$$\Delta p_{\Phi} = \frac{\frac{\sum_{t=2}^{n} |P_t - P_{t-1}|}{n-1}}{P_{inst}} \cdot 100 \quad [\%] \tag{6}$$

The second indicator for dynamic power changes analysis will be square root of summed squared changes per day (related to installed power) in %:

$$s_P = \frac{\sqrt{\frac{\sum_{t=2}^{n} (P_t - P_{t-1})^2}{n-1}}}{P_{inst}} \cdot 100 \quad [\%] \tag{7}$$

In both cases *n* (-) is the number of measured data on a given day [10].

Table 1. Parametres of analysed PVPPs

Analysed PVPPs	**PVPPs**	
	PVPP no.1	***PVPP no.2***
Installed power Pinst [kW]	16.2	800
Technology of PV panels	Polycrystal	Polycrystal
Azimut [°]	210	180
Slope [°]	42	35
Technology of inverters	One 17 kW inverter	47 psc of 17 kW inverters

For analysis below, measurements from two different PVPPs placed relatively close to each other (10.8 km) were used. Parameters of PVPPs are shown in Tab. 1. The weather conditions were analysed as being very similar for relevance of comparison.

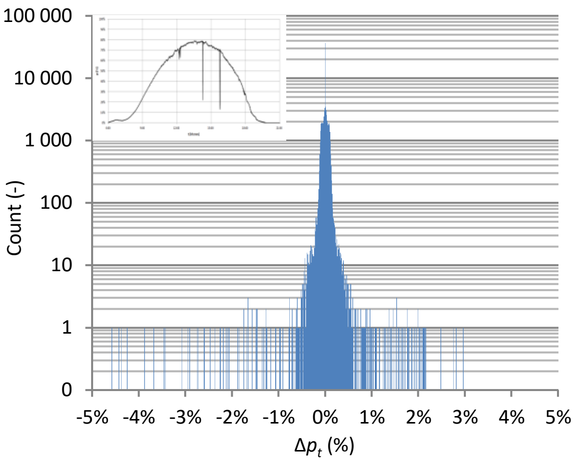

Figure 4. Statistical frequency of power changes in 1 second period—sunny day (PVPP no. 1)

In Figs. 3, 4, 5 and 6 statistical expressions of changes in frequency of PVPPs are depicted. These power changes are expressed as Δp_t and they are divided into intervals of 0,01% from installed power (interval of 0—0.01%, 0.01%—0.02%, 0.02—0.03% and so on).

In Figs. 3 and 4 it is visible that the power change between two measurements in a row was not greater than ±5% (only 1 measured point is higher in Fig. 4) of installed power during the sunny day. (The course of the power output of that day is displayed on the top of graph's). The results and indicators are shown in Tab. 2.

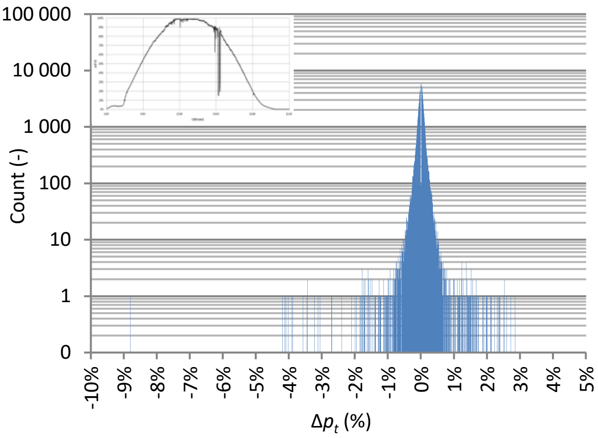

Figure 5. Statistical frequency of power changes in 1 second period—sunny day (PVPP no. 2)

The statistical expression of frequency of changes for both PVPPs are almost the same during sunny days. On the other hand, the power changes during a partly cloudy day were significantly higher and more frequent (Fig. 5 and 6).

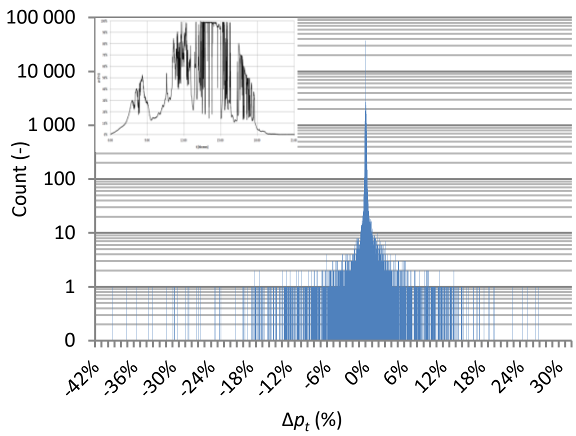

Figure 6. Statistical frequency of power changes in 1 second period—partly cloudy (PVPP no. 1)

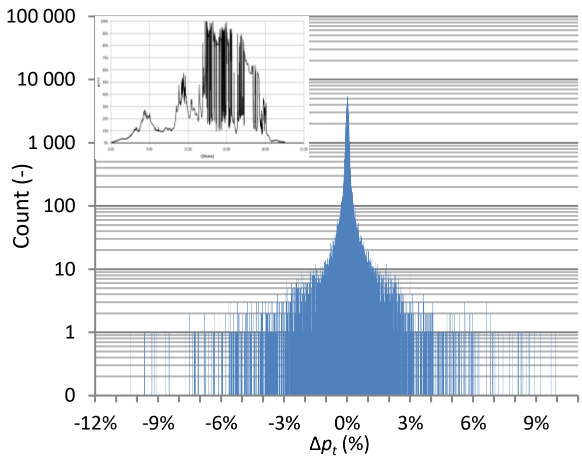

Figure 7. Statistical frequency of power changes in 1 second period—partly cloudy (PVPP no. 2)

The larger PVPP needs a larger cloud for the panels to be totally overlapped. Similarly, at the same wind speed (rather same cloud movement speed), the total overlap of large PVPP is slower than total overlap of smaller PVPP. It means that larger PVPPs (extending in a larger area) will lower absolute power changes and thus should achieve better results of Δp_Φ and s_p. This hypothesis is confirmed by comparison of the statistical expression of changes in frequency of both PVPPs on partly cloudy day (Tab. 2).

Table 2. Results of analysis and value of dynamic changes indicators

Indicators	**Sunny day**		**Partly cloudy day**	
	PVPP no.1	***PVPP no.2***	***PVPP no.1***	***PVPP no.2***
Maximal positive change [%]	3.0		2.8	
Maximal negative change [%]	-4.6		-8.8	
Amount of changes upper than +10%	0		0	
Amount of changes under -10%	0		0	
Average of absolute values of power changes Δp_Φ	0.0347		0.0664	
Square root of summed squared	0.095		0.1277	

Indicators	Sunny day		Partly cloudy day	
	PVPP no.1	***PVPP no.2***	***PVPP no.1***	***PVPP no.2***
changes per day s_p				

V. PVPP AS A DEVICE IN SYSTEM OF SMART GRID

Operator of the transmission system orders in a way that each power plant with installed power higher than 50 MW has to provide supporting services in the *Operation rules* document [11]. It means, if more and more small power plants (with installed power under 50 MW) will be in place, and large fossil power plants will be closed, the regulation power of the power system will decrease. It will increase the demand for regulation power by installing new small non predictable or hardly predictable power sources (such as PVPPs and wind power plants). It is necessary to find a solution for this issue. One of the solutions could be joint regulation of various power plants within virtual power plants. If the aggregator will have more virtual power plants joined by an operation and optimization system, it could reach the required minimal capacities in *Operation rules* of transmission system operator [11]. Using an appropriate combination of hardly predictable power sources and systems with the possibility of accumulation, the system of a virtual power plant can be not only predictable, but also it can become an interesting player in the energy market. It is necessary to have at least one accumulation system with power regulation in the system of a virtual power plant. This accumulation system can be represented by various technologies: directly accumulated electric energy (batteries, bladder vanadium flow batteries and others) or power accumulation in primary sources (biogas, biomass and others). The regulation of supplied power from PVPP is technically possible, too. But it is not profitable due to the actual supporting system of RES in Slovakia.

VI. CONCLUSION

Statistical analysis mentioned above points out to dynamic changes of PVPP power supply during partly cloudy days. Those days are the most difficult for prediction. It was shown that PVPP with higher installed capacity showed lower dynamic output changes. For a small PVPP up to 10 kWp (residential PVPP), the second dynamic changes can be more than 30% during partly cloudy days. Although, the power consumption of households might change, too. As a result, the 15-minute integrated production mathematically covers the consumption, but on the other hand in some moments the consumption can exceed the production of PVPP or vice versa. However, the production and the consumption on electricity meter are the same during the 15-minute period.

PVPPs with installed power of 100 kW and more (some MW) have second dynamic power change lower than small PVPPs (of approx 11%). Although, this does not mean that their performance does not suddenly change in the event of a cloud crossing.

This comparison could be beneficial for virtual power plant operators, who have one or more PVPPs in their balance responsible party. It can be considered as a valid input for the virtual power plant operation.

One of the ways to become independent from importing fossil fuels is deployment of power plants which have primary sources in the inland. One of the benefits of RES power plants is that most of them have primary energy sources at the place or close to the place of consumption. They are independent of their primary energy source, but on the other hand they are dependent on weather and other hardly predictive conditions. Therefore, issues with supplied power fluctuation and the energy storage are required to be solved. Virtual power plants can bring solutions to these challenges and make the RES power plants more competitive against traditional power plants on the energy market.

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