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Energy storage system in connection with a PV power plant

***Abstract**. This paper deals with issues associated with operation a selected photovoltaic (PV) power plant with reference to negative impacts on the grid, where this power plant is connected to. The description provided deals with one of the potential solutions for the particular issues that is represented by an balancing of this diagram showing production outcome of this PV power plant by application of a suitable storage system (accumulator). Optimal dimensions of the accumulator have been determined using a simulator calculation with the aim to suppress the largest number of adverse return impacts from the PV power plant against the grid.*

***Streszczenie.** Analizowano związek między pracą wybranych źródeł fotowoltaicznych a negatywnym ich wpływem na sieć. Pomocnym może być wykorzystanie odpowiedniego systemu magazynowania energii. (**Magazynowanie energii w połączeniu z elektrownią fotowoltaiczną**)*

Keywords: Accumulator; Li-ion; Electric power storage; Photovoltaic power plant.
Słowa kluczowe: magazynowanie energii, źródła fotowoltaiczne.

Introduction

One of the best available renewable energy sources (RES) is the solar radiation with great potential and easy utility characteristics. However, this source is highly unstable in the environment of Czech Republic; it is dependent on existing weather conditions at the particular location. Photovoltaic power plants (PPP), which ensure conversion of this energy into electric power, have experienced very rapid boom over the recent period. The fact that the supply from these power plants is variable and unreliable is also expressed by adverse back effects on the grid connected to the PPP output. One of the options to reduce these effects is to proceed with storage (accumulation) and power produced by these during period of excess and its supply into the grid during period of lack. There is a wide range of storage systems, differing by the technology used only, that can be used for this purpose.

I. Reverse Effects of PPP on Grid

Assessment of reverse effects of selected PPP on the grid was conducted using approximately one month worth of measurements of electric values at the transfer point between PPP and the grid. The measurement values were considered to assess the quality of voltage in accordance with standard ČSN EN 50160 with attention paid mainly to the magnitude of voltage, rapid voltage changes, the rate of flicker perception and voltage unbalance. The selected PPP with total installed capacity of 40 kWp comprised mono-crystalline photovoltaic panels. It was connected to the grid (400 V), whereas the area was a small municipality supplied from the transformer rated 22/0.4 kV (250 MVA). The data measured was used to calculate the average daily power output supplied by the power plant into the grid (see Fig. 1). The maximum power delivered was 33.8 kW. Fig. 2 shows the amount of electric power produced by the power plant on individual days during the monitored period.

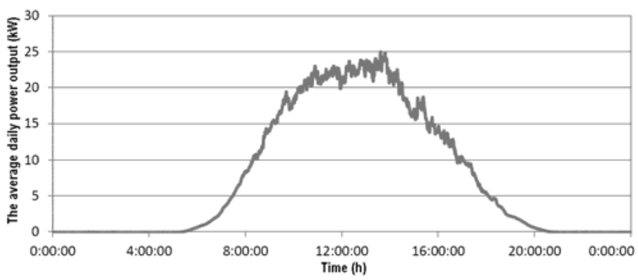

Fig.1. The average daily power output supplied by the PPP

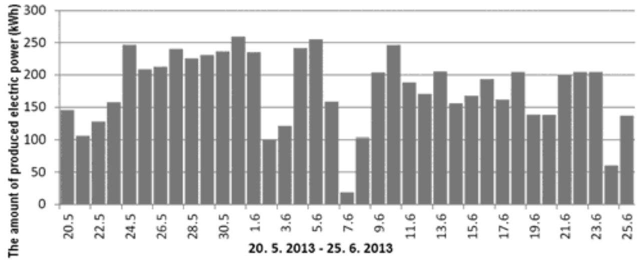

Fig.2. The amount of electric power produced by the PPP

Voltage Deviations

Under regular circumstances, every day must provide 95 % of average effective values of power supply for 10-minute measurement intervals with tolerance of ±10 %. [1] Values relevant to the selected period are shown in Tab. 1. As shown here, the threshold limits for phase voltage of 230 V (max. 253 V, min. 207 V) have not been exceeded.

Table 1. Voltage values obtained by measurement

U (100 %)	L1 phase	L2 phase	L3 phase
Average	235.0	231.6	234.2
Maximum	251.8	248.6	246.5
Minimum	221.9	214.1	224.5
U (95 %)	L1 phase	L2 phase	L3 phase
Average	234.3	231.2	233.7
Maximum	247.2	244.0	241.4
Minimum	222.1	216.1	224.5

Harmonic Distortion of Voltage

The Tab. 2 shows individual values of the total harmonic distortion of voltage (THD_U) per phase. The limit value used here is 8 % and it has not been evidently exceeded.

Table 2. The total harmonic distortion of voltage

THD_U (100 %)	L1 phase	L2 phase	L3 phase
Average	1.18	1.65	1.38
Maximum	1.99	2.64	2.11
Minimum	0.76	1.09	0.85
THD_U (95 %)	L1 phase	L2 phase	L3 phase
Average	1.18	1.61	1.35
Maximum	1.61	2.23	1.82
Minimum	0.75	1.09	0.84

Long-Term Rate of Flicker Perception

The long-term rate of flicker perception (Plt) must be less than or equal to "1" for 95 % of time (within any weekly period). Values stated in Tab. 3 show that the limit value is exceeded in all three phases on continuous basis. Flicker is an effect caused by fluctuation of voltage, which is demonstrated as a change of visual perception of humans. These disturbing changes have been induced by changes of the light flow over time, i.e. flicking of illuminating devices.

Table 3. The long-term rate of flicker perception

Plt (100 %)	L1 phase	L2 phase	L3 phase
Average	0.94	0.90	0.91
Maximum	2.50	2.91	4.94
Minimum	0.37	0.19	0.23
Plt (95 %)	L1 phase	L2 phase	L3 phase
Average	0.89	0.82	0.81
Maximum	2.07	2.42	2.31
Minimum	0.38	0.19	0.22

Rapid Voltage Changes

Low voltage defines the decrease of nominal voltage below 90 %. Excess voltage refers to increase of nominal voltage above 110 %. As the Tab. 4 shows, the measurement conducted on PPP recorded the total of 336 of excess voltage situations with the total duration of 2.187 hrs. (02:11:14).

Table 4. Rapid voltage changes (statistical data)

Phase	L1	L2	L3
No. of low voltage occurrences (-)	0	0	0
No. of excess voltage occurrences (-)	336	0	0
No. of downtime occurrences (-)	0	0	0
Total duration of low voltage (h)	0	0	0
Total duration of excess voltage (h)	2.187	0	0
Total duration of downtime (h)	0	0	0

Voltage Unbalance

The limit for voltage unbalance is 2 %. The values ranged within the interval of 0.10 - 1.13 % for 95% interval of values measured within the monitored period. The maximum value reached 1.7 %. There was everything in order with respect to voltage unbalance.

II. Accumulator Design

Any undesired reverse effects of the power plant onto the grid, as described in the previous chapter, can be reduced or totally eliminated by connecting a suitable storage system (accumulator). For block diagram showing connection between the accumulator with PPP and the grid see Fig. 3.

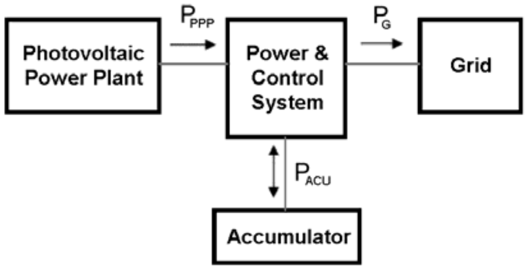

Fig.3. Block diagram of PPP with accumulation unit

The aim of the accumulation unit to strive towards even supply of power output into the grid provided it is restricted to a certain defined value. Any amount of electric power exceeding the production limit is stored in the accumulator on temporary basis. Once the output from selected PPP drops below the set value, the difference developed will be fed from the accumulator. That ensures preservation of power output supplied to the grid at constant value until exhaustion of the stored power. The accumulator will then be disconnected from the grid.

The accumulator is able to eliminate rapid increases and drops of output with relevant rapid changes in voltage. The supply of contact power output into the grid also enables to eliminate the flicker.

Determination of Accumulator Output Using Ideal Course of Output at PPP

The ideal course can be defined as the course of power output on an absolutely sunny day without any overcast conditions and any increases or drops of power output. Such ideal course is illustrated in Fig. 4 under the heading "Output supplied without accumulation". The Fig. 4 further shows evident settings of the limit of output (supplied into the grid) at the level of 20 kW. This value is achieved at the time of 9:00, when excessive electric power produced by the PPP starts charging the accumulator. Looking at the time after 16:30, the PPP is no longer able to supply the grid with the limit output and preservation of these values is aided by the accumulator. The supply of electric power in this mode lasts till 20:45, when the accumulator charge has dropped below the level set for is disconnection.

Table 5. Accumulator characteristics [3]

Accumulator capacity	Max.output - charging	Max.output - discharging	Max.dP_{15min}
(kWh)	(kW)	(kW)	(%)
60.2	11.8	-19.4	50.1

Simulation calculation was used to determine characteristics of accumulator for the described operating mode of PPP (see Tab. 5). The maximum utilised accumulator capacity has been set to 60.2 kWh. However, the capacity must be rated 15 % higher with respect to the depth of discharge; as well as 20 % lower with respect to capacity reduction due to ageing and cycling. [2]

When the 65% level of discharge is respected, the resultant value of accumulator capacity is 92.6 kWh. The parameter "Max.dP_{15min}" defines change in output with respect to the nominal capacity within 15-minute interval.

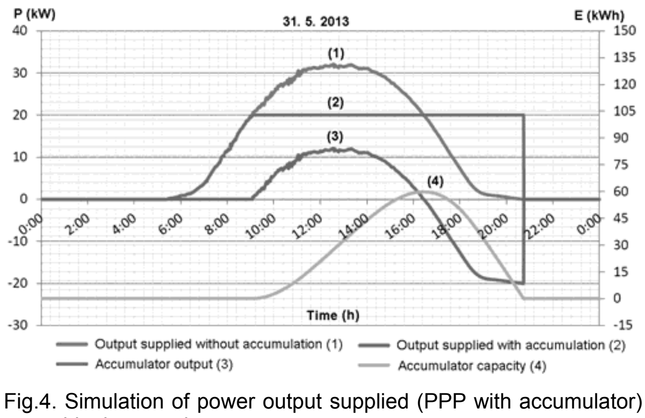

Fig.4. Simulation of power output supplied (PPP with accumulator) on an ideal sunny day

Accumulator Output and Capacity in Regular Operation

General determination of the accumulator capacity lies within the selected limit range of power output supplied. This level depends on the nature of power, whereas the four options to be considered are as follows:

- Absolutely sunny day: Ideal condition with virtually no fluctuation of power (as described in the previous chapter). The electric power supplied into the grid over selected period exceeds 250 kWh.
- A sunny day with slight overcast condition: Photovoltaic panels are subject to random shading resulting in subsequent drop of the power supplied. This day is characterised by more than 160 kWh of electric power supplied.
- A cloudy day with highly overcast condition: The power supplied is rather below-average nature and there are frequent output increases. The electric power supplied ranges within 100 - 160 kWh.
- Absolutely overcast day: The power supplied does not exceed 100 kWh. The power output never rises above 50 % of the nominal value for PPP. The role of accumulation is not substantial here, nevertheless the non-effective power can be stored for later supply as required.

A Sunny Day with Slight Overcast Condition

The simulation calculation was based on data measured on 29. 5. 2013. The optimal limit level of power supplied has been set to 18 kW here (with respect to values included in Tab. 6 and the maximum utilised accumulator capacity: 60.2 kWh, as stated in the previous chapter). As far as accumulator capacity is concerned, the optimal threshold limit corresponds with the value of 56.2 kWh.

The parameter "Max.dP$_{15min}$" without accumulation has been determined as 64.7 %, while the value with accumulation equalled to 45.2 % (see Tab. 6).

The Fig. 5 evidently shows that the reduced limit power supplied (18 kW) resulted in slight extension of the period for supply into the grid (till 20:55). Another evident aspect concerns the fact that almost all drops of the PPP power output have been eliminated.

Table 6. Accumulator characteristics for various limits values of power supplied (29.5.2013)

Limit of power output	Accumula-tor capacity	Max. output - charging	Max. output - discharging	Max.dP$_{15min}$ with accumulation
(kW)	(kWh)	(kW)	(kW)	(%)
30.0	1.0	3.0	-22.7	56.0
28.0	2.6	5.2	-20.7	37.7
26.0	9.0	7.2	-18.7	36.9
24.0	18.9	9.2	-16.7	44.1
22.0	29.7	11.2	-18.9	48.9
20.0	42.3	13.2	-18.8	47.6
18.0	56.2	15.2	-18.1	45.2
16.0	70.5	17.2	-16.1	40.2
14.0	85.8	19.2	-14.1	18.4
12.0	103.4	21.2	-12.1	13.4
10.0	121.9	23.2	-10.1	9.7

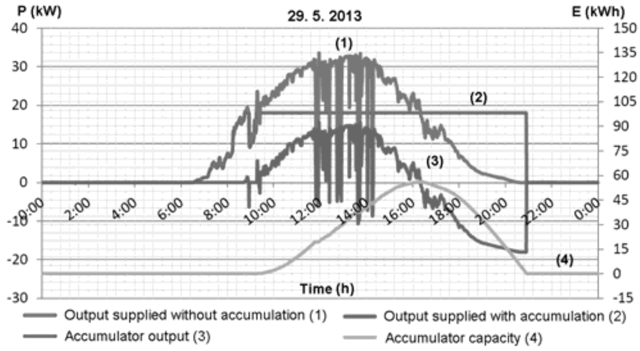

Fig.5. Simulation of power output supplied (PPP with accumulator) on a sunny day with slight overcast condition

A Cloudy Day with Highly Overcast Condition

The simulation calculation was based on data measured on 19. 6. 2013. The optimal limit level of power supplied has been set to 14 kW. As far as accumulator capacity is concerned, the optimal threshold limit corresponds with the value of 17.2 kWh. The parameter "Max.dP$_{15min}$" without accumulation has been determined as 33.0 %, while the value with accumulation equalled to 27.5 % (see Tab. 7). The Fig. 6 shows that the role of accumulation in this case is not as substantial, compared to previous situations.

Table 7. Accumulator characteristics for various limits values of power supplied (19.6.2013)

Limit of power output	Accumula-tor capacity	Max. output - charging	Max. output - discharging	Max.dP$_{15min}$ with accumulation
(kW)	(kWh)	(kW)	(kW)	(%)
30.0	0.0	0.0	0.0	33.2
28.0	0.0	1.1	-0.4	30.3
26.0	0.1	3.1	-1.5	26.5
24.0	0.4	5.1	-6.1	24.0
22.0	1.2	7.1	-6.1	20.9
20.0	2.4	9.1	-6.0	24.4
18.0	5.4	11.1	-11.9	29.7
16.0	11.0	13.1	-9.9	12.7
14.0	17.2	15.1	-9.0	27.5
12.0	24.6	17.1	-11.2	29.1
10.0	35.1	19.1	-10.0	25.1

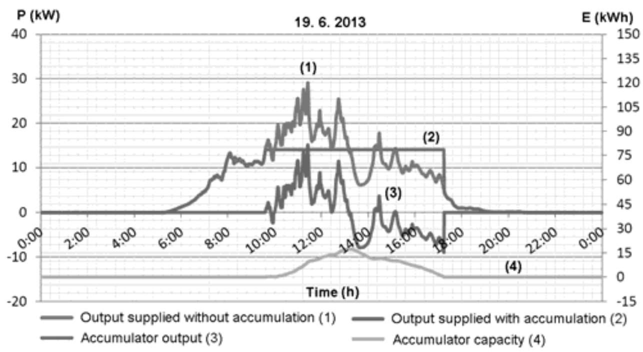

Fig.6. Simulation of power output supplied (PPP with accumulator) on a cloudy day with highly overcast condition

Summary of Simulation Calculations

As far as the simulation calculations completed together with the subsequent selection of accumulator (Li-ion) is concerned, the desirable option would like in operating the accumulation system of PPP with a rather lower level of power output threshold. The reason is that the accumulator type Li-ion, even though featuring quite a high number of working cycles and resistance to deep discharge, loses its capacity when cycled at the threshold of absolute discharge. That would occur in case the threshold level has been set too high and the course of power output from PPP would lie below the level for a longer period of time.

Accumulator Type

The most important aspects considered when choosing the type of accumulator suitable for linkage with a PPP include its efficiency and the number of operating cycles. Effective utilisation of solar energy cannot be considered for large losses due to higher cycle rate. For the above reason, Li-ion has been defined as the most convenient type of accumulator, which dominates especially for its high efficiency and longer service life (see Tab. 8).

Table 8. Parameters of Li-ion accumulator [4]

Efficiency	(%)	95
No. of operating cycles	(-)	8000
Service life	(year)	20
Response time	(s)	0.05
Response time	(%)	5
Price	(EUR/kWh)	423
Specific output	(W/kg)	280
Specific power	(Wh/kg)	130

Li-ion is a generally common and popular type of accumulator able to store between units of Wh and hundreds of kWh of electric power. Li-ion works on the principle comprising transmission of Lithium ion Li^+ via anhydrous electrolyte containing mainly Lithium salt dissolved in an organic solvent.

Parameters of Selected Accumulator

There are various versions of stationary and traction accumulators based on the Li-ion technology. The most common modification is $LiFeYPO_4$, which is also the most affordable one. Connection with the specific PPP has been made using this type of Li-ion accumulator accordingly. The Tab. 9 shows accumulators type $LiFeYPO_4$ with various parameters available on the market.

Table 9. LiFeYPO4 Accumulators [5]

Parameter	$LiFeYPO_4$ variants			
Voltage (V)	12	24	24	48
No. of cells (-)	4	8	8	16
Capacity (Ah)	200	200	400	200
Power (kWh)	2.5	5	10	10
Price (EUR)	990	2390	4607	4662

The service life of $LiFeYPO_4$ accumulator might account up to 8000 cycles, which corresponds to the service life of approx. 22 years with one cycle per day (with capacity drop to 80 %). The power storage system at the selected PPP has been fitted with this modification of $LiFeYPO_4$ accumulator: 24 V, 8 cells, 200 Ah, 5 kWh, 2390 EUR.

The electric power required from accumulation system (92.6 kWh) and the required power output supplied to the grid from power plant (20 kW) were used to design the final power storage system comprising 19 accumulators type $LiFeYPO_4$ (see Tab. 10).

Table 10. Resultant parameters of power storage system

Nominal voltage (V)	456
Nominal capacity (Ah)	200
Power (kWh)	95
Optimal discharge current (A)	100 (0.5 C)
Maximum discharge current (A)	2000 (10 C)
Optimal output (kW)	47.5
Maximum output (kW)	190
Price (EUR)	45385

Conclusion

Operation of photovoltaic power plants (PPP) is usually associated with negative reverse impact on the grid, to which these are connected. Due to non-conforming quality parameters of the electric power supplied, this solution employs mainly rapid voltage changes and the rate of long-term flicker perception. The said impact can be reduced by rendering the daily PPP production diagram even by application of a suitable power storage system. That results in restriction of the power supplied above certain defined threshold limit, when the excess production of electric power is stored in the accumulator. Once the output from PPP drops below the set value, the difference developed will be fed from the accumulator. That ensures preservation of power output supplied to the grid at constant value until exhaustion of the stored electric power. When designing an accumulation system for electric power storage, it is therefore necessary to start with definition of the optimal threshold level of power output supplied into the grid from specific power plant. The level then enables determination of specific parameters of accumulator. The unit apparently suitable for connection with PPP would be an accumulator based on Li-ion technology, e.g. $LiFeYPO_4$. The main advantage of this technology is the high efficiency exceeding 95 %, the relatively high number of operating cycles (up to 8000) and the last but not the least parameter is the long service life (approx. 20 years).

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