METHODOLOGY, MEASUREMENT AND ANALYSIS OF 20 kWp PV SYSTEM SERVICE CONDITIONS

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ABSTRACT

This article describes measurement methodology of large photovoltaic systems. The real data measured on 20kWp photovoltaic system installed on the faculty building in Bory and computed functionalities are displayed in the last paragraphs. Measurement records metered on this system served as input for numerical model of the PV system.

Keywords: *Photovoltaic system, Grid-on local power sources, V-A characteristics of PV cells, PV Enlargement*

1. INTRODUCTION

Demonstration photovoltaic system (installed power 20 kWp) dedicated for scientific purposes and for education at university is installed on the roof of new building of FEL ZCU in Pilsen.

PV system is connected to supply network and annually produces more than 20 000kWh of electricity. Actual values of produced energy and selected parameters of the system are presented on display unit in the faculty entrance hall. The data are stored in computer for additional elaboration and analyses. Small 1-axis tracking system for 2 PV panels serves for particular measurements. This unit is controlled via PC in the laboratory. Students can directly select configuration of the measurement.

Installation of the PV system was supported from SFZP CR within project “Sun into schools”, within “State program for energy savings and renewable energy usage” and within European project “PV Enlargement”.

Overall 1 150 kWp in 32 photovoltaic systems (located in 22 technical universities in EU and EU candidate states) was installed within this project. Goal of the project was demonstration of highly effective and innovative PV technologies in 10 European countries, public opinion evaluation, solar electricity highlighting, knowledge and technical-scientific finding exchange between academics and producers in EU, contribution to EU objectives, European industry evaluation, employment rate enhancement, renewable energy sources expansion, energy sources diversification and propagation of social and economical consistency between EU and EU candidate states.

Company WIP Munich was the coordinator of EC and company Solartec s.r.o. from Roznov pod Radhostem was coordinator in CR. This company has installed the PV system on FEL, ZCU in Pilsen.

2. 20 kWp PHOTOVOLTAIC SYSTEM

192 pc of monocrystalline silicon PV panels Isofoton I-110 (total output 21120Wp) are used in power segment of the system. Panels are distributed into 8 separate groups (photovoltaic array E1 – E8). Each photovoltaic array is separately connected to its own inverter Sun Power SunProfi SP2500-450 equipped with IGBT transistors. Produced electrical energy is supplied to low-voltage grid via switch board RO 02.5. Maximum output power (AC side) is P_{iac} = 19120 W. Panels are southbound orientated and mounted in declination 45° (see Fig. 1).

Fig. 1 20 kWp photovoltaic system

Grid phasing is provided separately by each inverter, which simultaneously provide their automatic switch-off in case of voltage dip. Therefore no voltage (dangerous voltage) is supplied to grid in case of main grid failure. Configuration of the arrays (E1 – E8) is described in Table 1. Block scheme of photovoltaic arrays wiring and block scheme of inverters wiring is shown in Fig. 2 and Fig. 3.

Table 1 Configuration of 20 kWp PV system

	PV	Panel type	Inverter	P_{mpp} [Wp]	U_{mp} [V]	U_{0c} [V]
E1	3x 24	Isofoton I-110	SunProfi SP 2500-450	2544	278	343
E2	3x 24	Isofoton I-110	SunProfi SP 2500-450	2544	278	343
E3	3x 24	Isofoton I-110	SunProfi SP 2500-450	2544	278	343
E4	3x 24	Isofoton I-110	SunProfi SP 2500-450	2544	278	343
E5	3x 24	Isofoton I-110	SunProfi SP 2500-450	2544	278	343
E6	3x 24	Isofoton I-110	SunProfi SP 2500-450	2544	278	343

E7	3x 24	Isofoton I-110	SunProfi SP 2500-450	2544	278	343
E8	3x 24	Isofoton I-110	SunProfi SP 2500-450	2544	278	343

Each array is complemented with 3 pc of surge guards DEHNguard T320 a 3 pc of protecting – backward diod BY 550-600. Inverters switching-off (including lock-off from DC power supply – photovoltaic array) is provided with 2-pole circuit brakers.

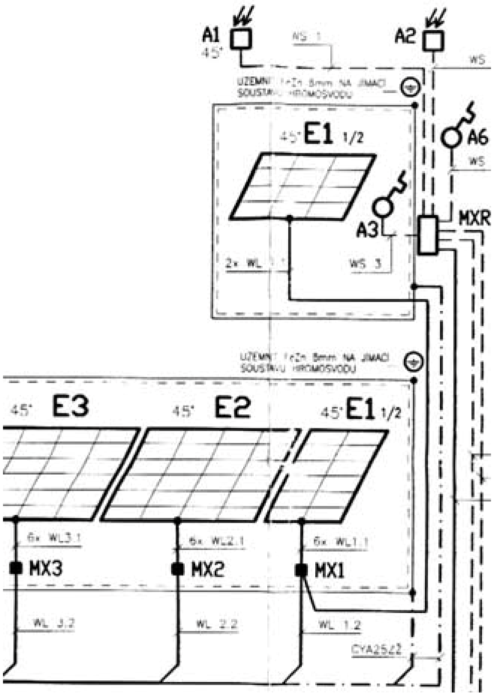


Fig. 2 Block scheme of PV arrays wiring

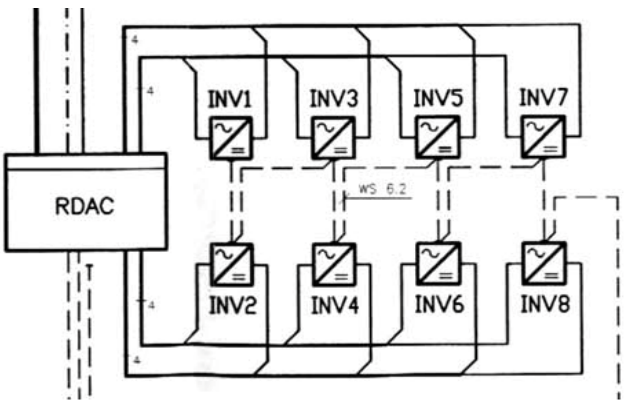


Fig. 3 Block scheme of inverters wiring

Switch board RDAC is equipped with electric supply meters with accessories for produced energy measurements. Extensive measurements are proceeded on this equipment. Instrumentation segment of the system allows measurement of all service quantities including rate analysis in connection point.

3. MEASUREMENTS OF SERVICE CONDITIONS AND VALUES

This photovoltaic systems serves except electricity supply especially for experimental purposes. Main measured values are:
array insolation [W/m2]
temperature of insolation sensor [°C]
global insolation [W/m2]
temperature of photovoltaic panel [°C]
DC current - array E8 [A]
DC voltage – array E8 [V]
power - array E8 [W]
temperature [°C]
total produced energy [kWh]
influence on grid (U, I, f, cosφ, THDi, THDu…)

Influence of the system on supply network is measured with analyser Unilyzer 900F, which operations agree with EN 50081-1,2 a EN 50082-1,2 (electromagnetic compatibility), EN 50160 (voltage measurements), IEC 61000-4-7 (harmonic analysis) and IEC 61000-4-15 a IEC 60868 (flicker measurements).

Meteorological station Vantage Pro 6310 is operated concurrently with this instrumentation system. It allows more detailed measurements of some values and next extends spectrum of measured values for photovoltaic system analysis.

3.1. Measurements of basic values

Measurements of basic values performed on this system reassume the long-time measurements performed in cooperation with ZCE Information center. Accurate data of solar insolation during each year season were recorded during these measurements. Average values of insolation, real usable energy, dimension and curve of air-pollution factor were computed from these data. Table 2 demonstrates month averages, month maximum and minimum of measured solar insolation compared with theoretical values. Relevant data are under consideration just between sunrise and sunset. Theoretical values are under consideration for the same azimuth and declination of insolated surface and for air-pollution factor valid for city [6].

Table 2 Intensity of solar radiation

	I.	II.	III.	IV.	V.	VI.
I_{teor} [W/m^2]	412	490	558	580	600	590
I_{ave} [W/m^2]	388	456	551	564	589	587
I_{max} [W/m^2]	407	471	553	571	602	589
I_{min} [W/m^2]	381	449	448	557	586	583
	VII.	**VIII**	**IX.**	**X.**	**XI.**	**XII.**
I_{teor} [W/m^2]	600	580	558	490	412	344
I_{ave} [W/m^2]	582	565	541	482	398	322
I_{max} [W/m^2]	586	573	552	485	403	329
I_{min} [W/m^2]	579	560	532	476	390	315

Table 3 demonstrates in the same way air-pollution factor. Comparison of measured and theoretical values [6] shows also all in all good situation in air pollution in Pilsen. Good dispersion conditions are especially in warmer months.

Table 3 Air-pollution factor

	I.	II.	III.	IV.	V.	VI.
Z_{ave}	3,15	3,21	3,04	3,10	3,07	3,02
Z_{min}	3,03	3,12	3,03	3,06	2,99	3,01
Z_{max}	3,20	3,26	3,74	3,14	3,09	3,04
Z_{city}	3,10	3,20	3,50	4,00	4,20	4,30
Z_{land}	2,10	2,20	2,50	2,90	3,20	3,40
Z_{mnts}	1,50	1,60	1,80	1,90	2,00	2,30
	VII.	**VIII.**	**IX.**	**X.**	**XI.**	**XII.**
Z_{ave}	3,11	3,09	3,10	3,05	3,09	3,14
Z_{min}	3,09	3,04	3,04	3,03	3,06	3,10
Z_{max}	3,13	3,12	3,16	3,09	3,14	3,19
Z_{city}	4,40	4,30	4,00	3,60	3,30	3,10
Z_{land}	3,50	3,30	2,90	2,60	2,30	2,20
Z_{mnts}	2,30	2,30	2,10	1,80	1,60	1,50

Examples of real measured curves of solar radiation are displayed in Fig. 4 (winter season) and Fig. 5 (summer season). Graphs serve also for comparison between global intensity of solar radiation and intensity of radiation incidenting surface of PV cells and weather influence.

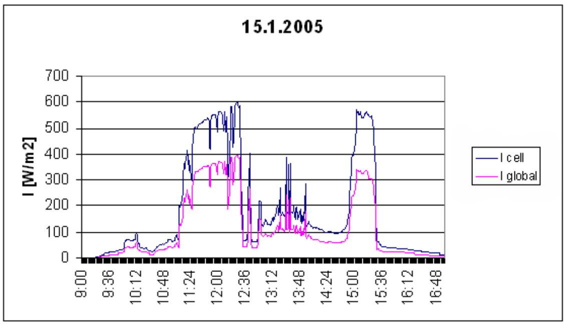


Fig. 4 Solar radiation – winter season

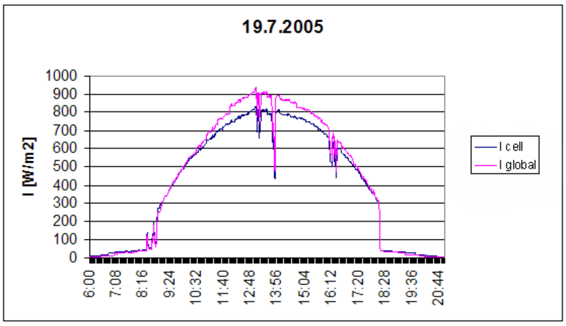


Fig. 5 Solar radiation – summer season

3.2. Influence on supply network

Supplementary measurements of electrical values being in progress on switch board RDAC test influence of monitored system on supply network. Average, minimal and maximal values of voltage and current in each phase are the most important from the measured values. All measured data are recorded in 1min interval. Higher harmonics volume is analysed from the logged data using Fourier analyses. The analyses are computed up to 50^{th} harmonics (according to standard).

Results of these measurements serves for quality control of electrical energy produced into ZCU supply network and for coincidence certification in the meaning of electromagnetic compatibility according the standard ČSN EN 50160. According the long time records, it is possible to say, that monitored values don't trespass values permited by the standard ČSN EN 50160 . Typical result of these measurements is shown in Fig. 6 (Umin).

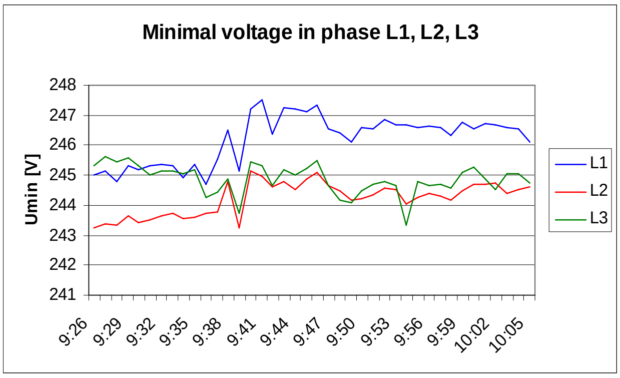


Fig. 6 Minimal voltage in phase L1, L2, L3

Fourier analyses output served, except other, for building and improvement of AC modul of the photovoltaic system numerical model. Typical example of measured voltage spectral components is displayed in Fig. 7. Current spectral components in each phase are shown in Fig. 8. Amplitudes of the 1^{st} harmonics are not displayed because of better visualisation. The amplitude of this component is not comparable to other harmonics, above all in output voltage, where hundreds order to tenths of volts. Visualisation of this component would lead to losses of details in right part of the spectrum.

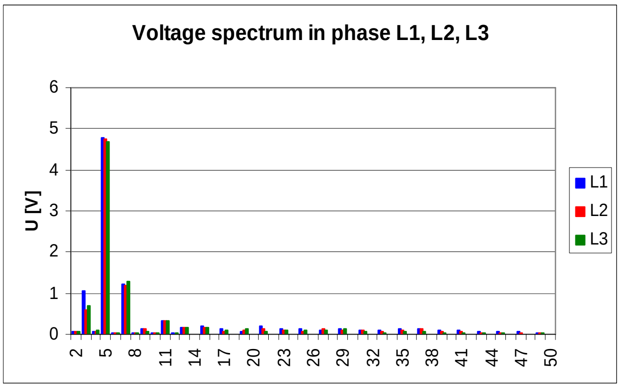


Fig. 7 Voltage spectral components in phase L1, L2, L3

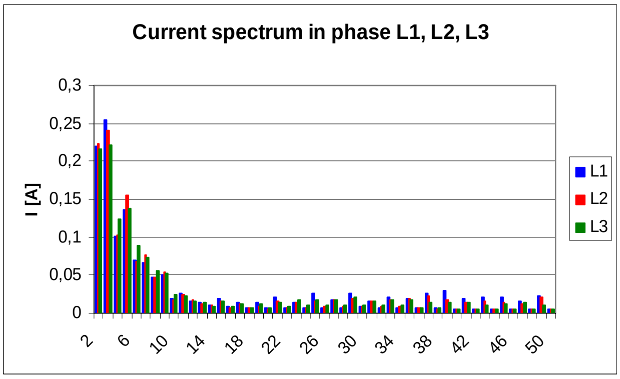


Fig. 8 Current spectral components in phase L1, L2, L3

3.3. Measurements of produced electricity

The system was connected to grid on March 12th 2004 and average annual production of the system oscillates around 23000 kWh. Detailed values (including mensural values referenced to 1kW$_p$ and 1 m^2 are shown in Table 4.

Table 4 Annual electricity production

	Production [kWh]	Mensural production [kWh/kW$_p$]	Mensural production [kWh/m^2]
2005	23795	1126,66	145,80
2006	23873	1130,35	146,28
2007	23532	1114,20	144,19

Relation of electricity production and the year season and comparison with theoretical values presents graph in Fig. 9. Low production in winter months is evident. This is caused by either unsuitable orientation of the system (small inclination for winter months) or unfavourable weather typical for this season. The production is almost constant during the rest of year, what is caused again by unsuitable orientation of the system (high inclination for summer months) and, above all, by high working temperatures of the cells in the hottest months.

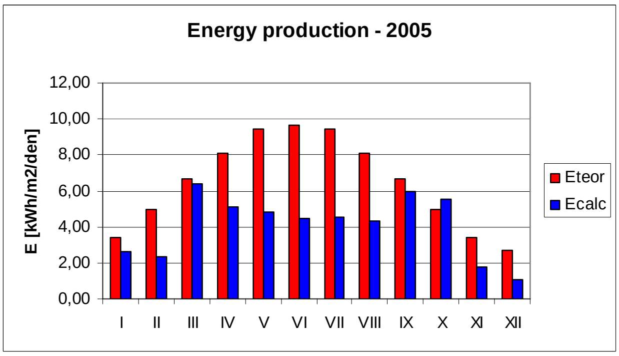


Fig. 9 Relation of the production and year season

3.4. Measurements of service dependencies

Maximal and average values of solar radiation incidenting surface of the cells during each season and real exposure times could be easily get from the measured curves. Very interesting is the fact, that the run of incidenting radiation intensity in spring is almost similar to the run in summer, what justifies used orientation of the system (inclination of 45°). Maximal values of incidenting radiation are higher in spring than in summer, when higher values of global radiation could be recorded. This illusory paradox could be explained with inclination used at the panels. The Sun is very high over the horizon during summer months and includes sharper angle with panels, what decreases maximal expositions. Similar situation like during spring is during fall, when the Sun is again lower over the horizon. Imaginary envelope of the curves is dramatically affected by the weather and the comparison is not so evident. Inclination of the system, which is a bit unsuitable in summer increases efficiency in winter (compared to lower inclination), when the Sun is very low over the horizon and includes an open angle with the panels, what increases the insolation of the cells.

The graphs show, that temperature of panels doesn't rely just on intensity of insolating radiation. Considerable difference of working temperatures during summer and spring (while almost the same insolation of incending radiation) is evident in Fig. 10 and 11. External cooling of the cells is very important too and depends on the temperature, humidity, and wind speed and directions. Lower temperatures during the spring allowing better cells cooling then during high summer temperatures. Thermal persistence of photovoltaic panels delaying the temperature curve behind the insolation curve could be observed in pictured charts. The insolation curve equalize the thermal curve. Next phenomenons (above all changing wind) distort the thermal curves, that don't fit (fully) the radiation insolation curves. Computation of the system 's cooling effect would be very complicated and probably inaccurate.

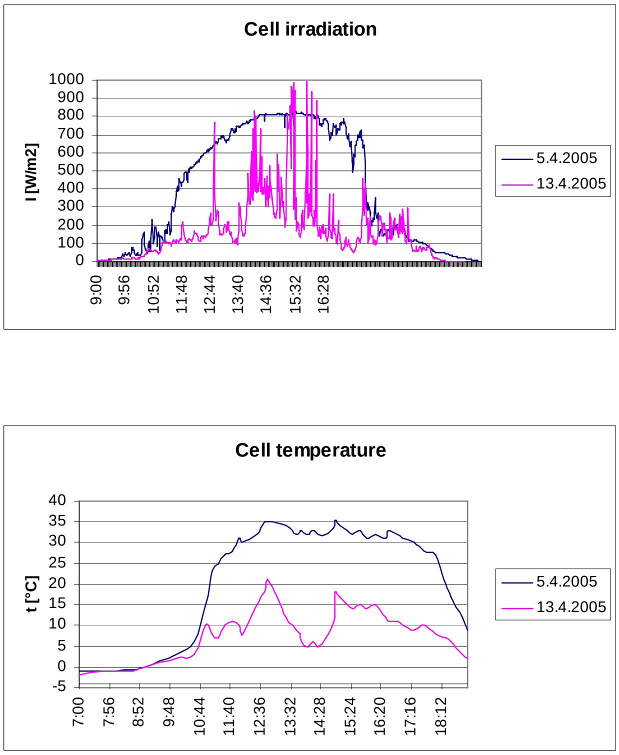
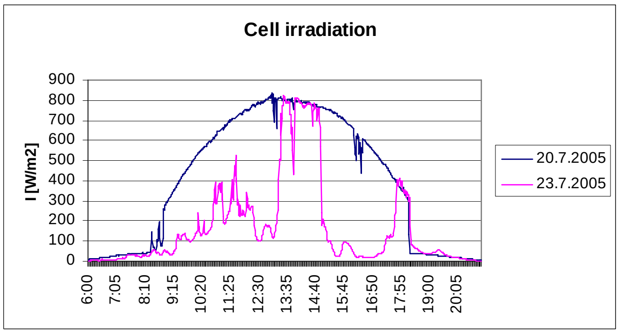


Fig. 10 Incidenting radiation and cell's temperature (spring)



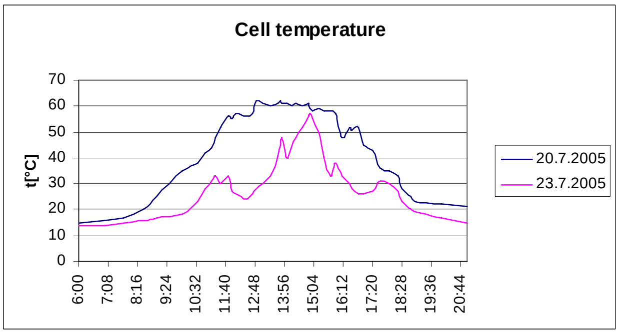


Fig. 11 Incidenting radiation and cell's temperature (summer)

Big differences of working temperatures affect the final efficiency of the system, as demonstrates chart in Fig. 9, which compares real produced energy and theoretically possible energy (while constant efficiency of the cells – 15%).

Examples of service dependencies measurements and efficiency computations are presented in Table 5 – 8. Presented data shown in the tables cover almost full range of service conditions. Table 5 (winter season) show, that the highest efficiency is reached in colder periods (while relatively low incidenting radiation), when the cells are undercooled and having smaller inner resistance. Vice versa in summer months, when the maximum of solar energy is available, decreases the high temperature of the cells (even 60°C – see Table 7) their efficiency under 10%.

Last rows of Tables 5 – 8 demonstrate total efficiency of the whole photovoltaic system and also document almost constant efficiency of used inverters.

Table 5 Efficiency of the PV system – winter season

12.1.2006 10:00, 2°C, clear weather			
I_{cells} [W/m^2]	454,1	453,2	461,3
I_{global} [W/m^2]	443,3	442,8	454,1
P_{DC} [W]	982,3	981,6	988,4
P_{AC} [W]	891,7	891,5	896,2
t_{cells} [°C]	12,2	12,2	12,4
η_{PV} [-]	0,1460	0,1461	0,1463
η_{total} [-]	0,1362	0,1362	0,1366
20.1.2006 10:30, -2°C, cloudy			
I_{cells} [W/m^2]	208,9	211,6	213,7
I_{global} [W/m^2]	207,5	210,0	212,4
P_{DC} [W]	398,3	403,6	404,1
P_{AC} [W]	297,6	302,4	306,3
t_{cells} [°C]	3,1	3,1	3,2
η_{PV} [-]	0,1256	0,1259	0,1259
η_{total} [-]	0,1161	0,1163	0,1164

Table 6 Efficiency of the PV system – spring season

16.5.2006 11:00, 19°C, clear weather			
I_{cells} [W/m^2]	581,6	591,2	560,7
I_{global} [W/m^2]	595,9	605,5	565,6
P_{DC} [W]	1290,8	1310,4	1240,4
P_{AC} [W]	1178,9	1195,7	1133,5
t_{cells} [°C]	39,7	40,8	41,9
η_{PV} [-]	0,1088	0,1087	0,1084
η_{total} [-]	0,0994	0,0991	0,0991
28.4.2006 11:00, 13°C, somewhat cloudy			
I_{cells} [W/m^2]	488,2	499,9	510
I_{global} [W/m^2]	531,1	540	547,6
P_{DC} [W]	1106,5	1131,9	1150,6
P_{AC} [W]	1006,9	1031,2	1049,1
t_{cells} [°C]	29,6	29,8	31
η_{PV} [-]	0,1111	0,1110	0,1106
η_{total} [-]	0,1011	0,1011	0,1008

Table 7 Efficiency of the PV system – summer season

26.6.2006 13:00, 30°C, sunny weather			
I_{cells} [W/m^2]	975,9	981,5	960,2
I_{global} [W/m^2]	908,2	908,2	887,5
P_{DC} [W]	1929,8	1956,4	1922,6
P_{AC} [W]	1755,9	1779,1	1750,7
t_{cells} [°C]	58,4	58,9	59,1
η_{PV} [-]	0,0969	0,0977	0,0982
η_{total} [-]	0,0882	0,0889	0,0894
12.6.2006 9:30, 21°C, somewhat cloudy			
I_{cells} [W/m^2]	602,5	605,3	613,4
I_{global} [W/m^2]	620	621,4	627,6
P_{DC} [W]	1322,9	1331,2	1347,7
P_{AC} [W]	1208,4	1217,9	1229,5
t_{cells} [°C]	40,5	40,6	40,9
η_{PV} [-]	0,1076	0,1078	0,1077
η_{total} [-]	0,0983	0,0986	0,0983

Table 8 Efficiency of the PV system – fall season

20.9.2006 13:00, 22°C, sunny weather			
I_{cells} [W/m^2]	870,1	912,7	917,5
I_{global} [W/m^2]	834,4	871,6	875,1
P_{DC} [W]	1895,5	1979,7	1981,9
P_{AC} [W]	1728,5	1801,3	1803,4
t_{cells} [°C]	46,1	50,6	51
η_{PV} [-]	0,1068	0,1063	0,1059
η_{total} [-]	0,0974	0,0967	0,0964
8.10.2006 11:00, 12°C, fog			
I_{cells} [W/m^2]	318,0	323,3	299,5
I_{global} [W/m^2]	347,7	365,6	355,3
P_{DC} [W]	722,7	717,8	655,9
P_{AC} [W]	651,4	648,2	591,2
t_{cells} [°C]	19,6	19,8	19,8

η_{PV} [-]	0,1114	0,1088	0,1074
η_{total} [-]	0,1004	0,0983	0,0968

4. RESUME

Presented measurements and results served to create methodology of PV systems service conditions evaluation and to build a numerical model of real operated photovoltaic system. Functionality of the model was tested on these measurements. Final model of the 20 kWp photovoltaic system (including model of inverters) works with inaccuracy less than 4% in the whole spectrum of output current and voltage up to 50th harmonic in the whole range of service conditions.

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BIOGRAPHIES

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Jan Škorpil was born on 18. 8. 1941. In the 1964 he received the M.Sc. (Ing.) degree with distinction at the Technical College in Pilsen, at the Department of Power machinery engineering. Then he worked as a plant engineer at the power and heating station of Chemical plant in Záluží. Since 1966 to 1971 he was a senior lector at the department of Power machinery engineering at the Technical College in Pilsen. Since 1971 to 1981 was a special worker for teaching technology, since 1981 he works at Power engineering department of Electric Engineering Faculty of West Bohemian University in Pilsen. He finished PhD (CSc.) study in 1989. Since 1991 he is associate professor (Doc.) and since 2006 he is professor. His branch area is power station equipment, renewable energy sources and environmental protection.