

PV Emulator

Case Study

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Abstract – *The photovoltaic emulator (PV emulator) described in the paper is used for laboratory exercises in the courses Renewable Energy Sources and Emergency/Standby Power Supply Systems in the Graduate (Master) Studies in Electrical Engineering – Power Systems Engineering and Principles of Power Electronics in the Undergraduate (Bachelor) Studies in Electrical Engineering as well as for scientific research relating to setting an optimal photovoltaic system for regional climatic elements. The paper gives a detailed description of subsystems of the PV emulator as well as a possibility of DC programmable sources of the subsystem. It is shown how electricity production from the photovoltaic system with peak power of up to 12 kW can be emulated by using the PV emulator for one chosen day in the month.*

Keywords – *emulation, measurement, photovoltaic system, set up, v-I photovoltaic module characteristic*

1. INTRODUCTION

An increasing interest in and demand for photovoltaic systems have set new requirements for PV equipment manufacturers. It was necessary to find more sophisticated ways of testing photovoltaic equipment, primarily with regard to inverters and maximum power point track (MPPT) systems. The output power of photovoltaic modules is influenced by two factors [1]: solar radiation (isolation) and temperature of a PV cell, i.e., PV module. The previous generation of PV electronic equipment was tested under real weather conditions, as the first generation systems were less powerful. However, it is often difficult to carry out testing under real operating conditions on modern PV systems of 100 kW or more, due to the issues of space, price and dependence on weather conditions, the latter becoming the dominant factor when testing such equipment.

These are the very reasons for the emergence of the need to use programmable DC sources emulating the characteristics of PV modules, which gave them their name – photovoltaic module emulators. Such sources are used to further test and develop electronic equipment built into photovoltaic systems, such as inverters and MPPT systems. There are currently several types of programmable DC sources on the market that can emulate photovoltaic modules, with power outputs ranging from several kW up to 2000 kW [2-4].

Once inverters and MPPT systems have been tested in this manner, conditions are created for a more important task – an evaluation of electrical power produced by a selected photovoltaic system. An electronic system used for the evaluation of electrical power generated by photovoltaic modules is called a photovoltaic emulator. There are several different concepts of

PV emulator realization. One of those is aimed at simulation, where PV emulator modeling is used in special software, such as e.g. MATLAB [5]. It is typical of this approach that physical quantities – currents and voltages – are scaled to amounts that are safe for handling and accessible for measurements [6]. One such system is Typhoon HIL [7], which supports this simulation-based approach with its HIL emulator series.

For the emulation of photovoltaic systems, the authors have chosen another, energy-based approach, where instead of scaling currents and voltages, real voltage and current values would be obtained by measuring. Measurements of the $v-i$ characteristic of photovoltaic modules should be obtained in advance for this approach. Therefore, database [8] is used. Measurement results stored in database were used as input parameters of the PV emulator.

2. SET UP OF PV EMULATOR

A laboratory model of a PV emulator used in this paper consists of two programmable DC sources, one KACO inverter and necessary protective devices and it is shown in Fig.1. Programmable DC sources are connected to an AC network supply, and they convert AC currents into DC currents. DC currents on the output of DC sources are defined by characteristics set up in the PV emulator. Programmable DC sources LAB/HP 101000 by ET SYSTEM are used. They generate DC currents of up to 10 A and voltages of up to 1000 V and can simulate a photovoltaic module. Compared to photovoltaic modules, output parameters of programmable DC sources LAB/HP 101000 are independent of climatic elements (sun isolation, temperature, etc.). Programmable DC sources LAB/HP 101000 are used as an input subsystem of a PV emulator for testing photovoltaic electronic equipment like inverters or an MPPT control circuit, because they can always give output characteristics of a photovoltaic model needed for testing.

The inverter is one of the main subsystems of a PV emulator. KACO 12.0 TL3 inverter is selected due to the possibility of using two MPPT inputs, Fig. 2. It means that the inverter KACO 12.0 TL3 can be supplied by two programmable DC sources. DC power produced from programmable DC sources is converted into AC power by using the KACO 12.0 TL3 inverter. The converted AC power is submitted into the electric power system.

The connection of programmable DC sources on the connection board of the inverter is shown in Fig. 2. The acronym MPPT stands for Maximal Power Point Tracking and it marks that operating point in which the photovoltaic module or string of photovoltaic modules gives the maximal power at a given load. The first MPPT system of the inverter is marked with letter A and the second with letter B. They have DC+ and DC – inputs. It is important to take care of the right polarity by connecting programmable DC sources LAB/HP 101000 on the MPPT system inputs.



Fig. 1. Laboratory set up of a PV emulator

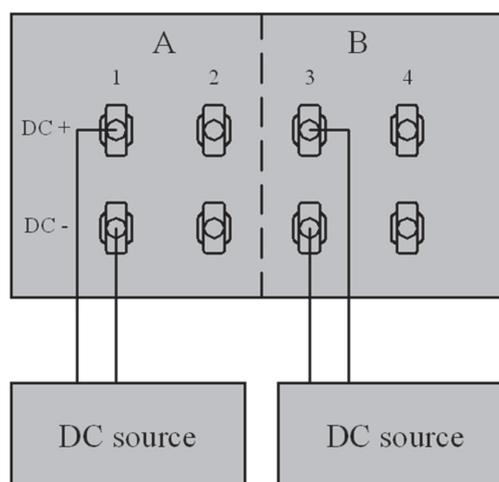


Fig. 2. The connection of two DC sources to two MPPT inputs

The output voltage of the KACO 12.0 TL3 inverter is synchronized with the power grid voltage. Therefore, there is no need for additional synchronization electronic equipment. The ON/OFF switch enables turning on to work on the grid in any moment as well as turning off for maintenance. The value of produced energy on daily, weekly and monthly base as well as all recorded power data can be recorded and transferred to a USB device which is connected to a separate connector. The KACO 12.0 TL3 inverter also provides real time measurements, such as measurements of power produced instantaneously, voltages, currents, etc.

The schematic diagram of a PV emulator used in this paper is shown in Fig.3. A differential current switch (RCD), an overvoltage protector (surge resistor) and fuses are embedded in the protective device box.

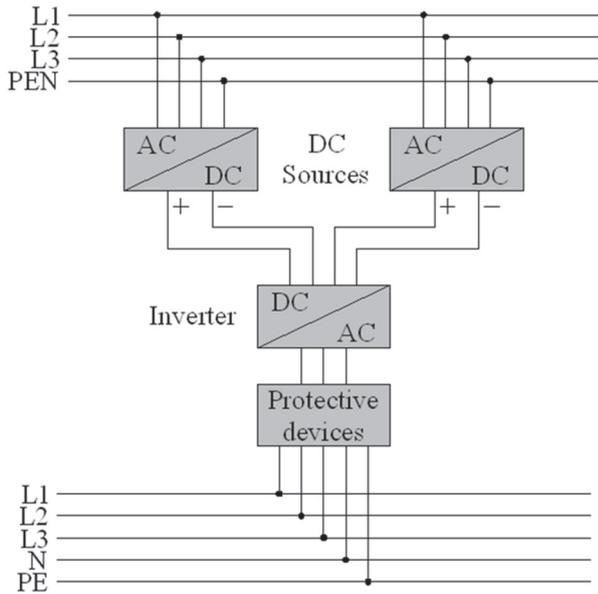


Fig. 3. The connection of two DC sources to two MPPT inputs

3. MEASUREMENT OPTIONS

A programmable DC source LAB/HP 101000 made by ET SYSTEM has five possible operating modes: UI mode, UIP mode, UIR mode, PVsim mode and Script mode. In UI operating mode, supply current (I) and supply voltage (U) are limited. In UIP operating mode, in addition to current and voltage, power (P) is limited as well. UIR operating mode simulates the operation of a real voltage source. PVsim operating mode is used for photovoltaic module simulations. For photovoltaic module simulation as well as for a string of photovoltaic module simulation, it is necessary to define the following four characteristic values: U_{OC} – open circuit voltage of the module, U_{MPP} – MPP module voltage, I_{SC} – short circuit current of the module, and I_{MPP} – MPP module current. In script operating mode, the DC source executes the program code from the SD card inserted in the SD-card slot on the DC source. The programmable DC source operating in script mode can be programmed for work in UI, UIP, UIR and PVsim modes.

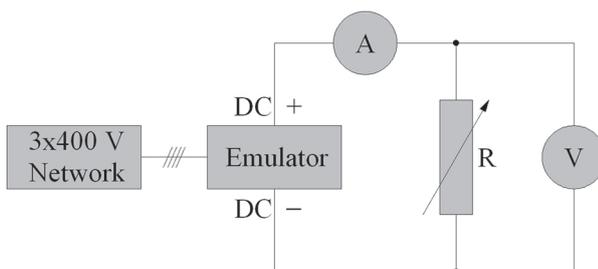


Fig. 4. Scheme for testing operating modes of a DC source

A schematic diagram of testing operating modes of a programmable DC source (UI, UIP, UIR and PVsim mode) is shown in Fig.4. The PV module emulator is connected to a three-phase AC supply system. A variable resistor R is connected to the DC source output as load. The load current and voltage are measured with the U - I method. The change in the load resistance R causes a change in load current and the operating point.

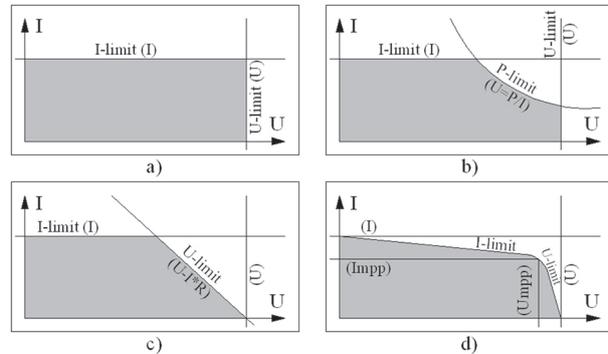


Fig. 5. Possible operating point areas for: a) UI mode, b) UIP mode, c) UIR mode and d) PVsim mode

Possible operating point areas for: a) UI mode, b) UIP mode, c) UIR mode and d) PVsim mode are shown in Fig.5., and they were colored gray. The load voltage is set on the x-axis and load current is set on the y-axis. This characteristic is called a v - i characteristic. The possible operating point area is colored gray. Every operating point area is limited by voltage (U -limit), current (I -limit) and/or power (P -limit). The v - i characteristic for PVsim operating mode and an operating point marked with a small white dot is shown in Fig.6.

The variable load resistance is set to 3.5Ω . The v - i characteristic of the photovoltaic module BISOL BMU-250 is simulated by PVsim operating mode of a DC source and it is shown in Fig.6.

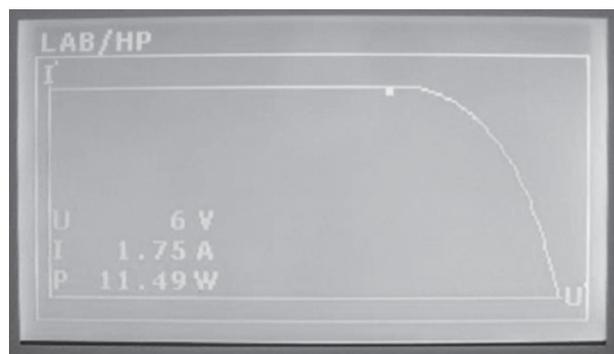


Fig. 6. v - i characteristics simulated by PVsim operating mode and operating point [9]

The voltages and currents of the simulated v - i characteristic of the photovoltaic module BISOL are scaled four times regarding a technical characteristic of measurement equipment. Sun insolation was 800 W/m^2 and the photovoltaic cell temperature was $44 \text{ }^\circ\text{C}$. Characteristic values of voltages and current of the simulated v - i

characteristic of the photovoltaic module BISOL were: $I_{SC}=7.08:4=1.77$ A, $I_{MPP}=6.68:4=1.67$ A, $U_{OC}=35.1:4=8.75$ V, $U_{MPP}=27.7:4=7$ V. The output power of a programmable DC source was 11.49 W and it was determined by load resistance. By changing the load resistance R , it can be observed that if, for example, the operating point is set to the current limitation straight line (I -limit) and load resistance decreases due to impossibility of further increase of current, the voltage of the emulator will increase and the operating point will move right along on the straight line or a curve defined by current limitation.

Apart from the aforementioned operation modes, the PV module emulator can also operate in the master/slave mode. This operating mode is used by linking up two or more programmable DC sources together. By this operating mode, one of the PV module emulators is the master and others are slaves. The parameters set on the master PV module emulator will be transferred automatically and set on every other linked PV module emulator.

4. EMULATION OF PV SYSTEM

It is necessary to know the basic properties of a PV system to perform emulation. Also, it is necessary to know specific characteristics of modules a PV system is made up of. Therefore, the PV system with peak power of up to 12 kW is chosen for emulation and PANASONIC VBHN240SE10 [10] modules are used as PV modules of the PV system. To be more specific, this PV system is built up of 50 modules and each has power of 240 kW.

The next step in emulating the PV system is to prepare input parameters for the PV module emulator. The basic and most important data necessary for performing module emulation are parameters of the v - i characteristic of the photovoltaic module. There are: open circuit voltage (U_{OC}), short circuit current (I_{SC}) and voltage and current (U_{MPPN} and I_{MPPN}) at maximum power point (MPP). Voltage and current of the string, U_{STR} , I_{STR} are obtained by using the following expressions:

$$U_{STR} = n \cdot U_{OC} [V] \quad (1)$$

$$I_{STR} = m \cdot I_{SC} [A], \quad (2)$$

where: n – total number of modules in series; m – total number of parallel branches with modules connected in series.

Values of voltage and current at MPP, U_{MPPN} , I_{MPPN} are obtained in the same way.

$$U_{MPPN} = n \cdot U_{MPP} [V] \quad (3)$$

$$I_{MPPN} = m \cdot I_{MPP} [A] \quad (4)$$

U_0 [V]	I_{KS} [A]	U_{MPP} [V]	I_{MPP} [A]	PAN _{ST1} [n]	PAN _{ST2} [n]	No.par [m]	U_{STR1} [V]	U_{STR2} [V]	I_{STR} [A]	$U_{MPP,ST1}$ [V]	$U_{MPP,ST2}$ [V]	$I_{MPP,STR}$ [A]
44.7	0.12	34.9	0.07	13	12	2	581.1	536.4	0.24	453.7	418.8	0.14
47.2	0.19	38.5	0.17	13	12	2	613.6	566.4	0.38	500.5	462	0.34
30	0.63	41.8	0.87	13	12	2	575	530	1.85	543.4	501.6	1.74
49.5	0.68	41.4	0.61	13	12	2	643.5	594	1.36	538.2	496.8	1.22
50.8	1.27	49.3	1.18	13	12	2	680	625	2.54	640.9	591.6	2.36
50	1.03	41.8	0.96	13	12	2	650	600	2.06	543.4	501.6	1.92
50.2	1.27	42.2	1.15	13	12	2	652.6	602.4	2.54	548.6	506.4	2.3
50.8	1.93	42.4	1.91	13	12	2	660.4	609.6	4.03	551.2	508.8	3.82
50.4	2.16	41.2	1.8	13	12	2	655.2	604.8	4.32	535.6	494.4	3.6
48.9	1.22	40.2	1.04	13	12	2	635.7	586.8	2.44	522.6	482.4	2.08
49.7	0.8	47.3	0.69	13	12	2	646.1	596.4	1.6	614.9	567.6	1.38
49.8	1.01	41.8	0.85	13	12	2	647.4	597.6	2.02	543.4	501.6	1.7

Fig. 7. Input data for PV system emulation

After the procedure of PV module emulation is described, emulation has been obtained for the selected PANASONIC VBHN240SE10 modules. The 12kW PV system consisted of 50 modules connected into 4 strings (2 strings with 13 modules and 2 strings with 12 modules). Data used for calculation of input parameters of the PV module emulator were taken from database [8] for the day 9 April 2014, and this is shown in Fig.7. The database was created in scientific research conducted under the IPA Cross-border Co-operation Programme Hungary-Croatia, project REGPHOSYS: Photovoltaic Systems as Actuators of Regional Development, with the Faculty of Electrical Engineering in Osijek as a project leader and the Hungarian Academy of Sciences, Center for Regional Studies, Pécs, as a project partner [11].

The calculated input data for PV system emulation, string voltage and string(s) current, and voltage and current at MPP for the first hour of emulation were obtained from:

$$U_{STR1} = n \cdot U_{oc} = 13 \cdot 44.7 = 581.1 V \quad (5)$$

$$I_{STR} = m \cdot I_{sc} = 2 \cdot 0.12 = 0.24 A \quad (6)$$

$$U_{MPP1} = n \cdot U_{MPP} = 13 \cdot 34.9 = 453.7 V \quad (7)$$

$$I_{MPP1} = m \cdot I_{MPP} = 1 \cdot 0.07 = 0.14 A \quad (8)$$

The input data are then entered in DC programmable sources and emulation was performed. To have emulation as accurate as possible, these data can be entered in the PV module emulator with different time intervals. After completing emulation of the PV system, all data on the DC or the AC side of the PV system can be downloaded from the inverter. These data are current and voltage of the strings, $I_{DC1,2'}$, $U_{DC1,2'}$, power of the strings $P_{DC1,2'}$, output values such as phase currents and phase voltages; $I_{AC1,2,3'}$, $U_{AC1,2,3'}$, total DC and AC power, P_{DC} , P_{AC} . As shown, all data are collected at intervals of 15 minutes.

Emulated electricity production was 23.11kWh, as Fig. 8. The efficiency of the inverter can be calculated from:

$$\eta = \frac{P_{AC}}{P_{DC}} \quad (9)$$

The efficiency rate of the inverter of this emulation was 98.7%. This data is used for analytical calculation of electricity production. The analytical method is obtained for two reasons. Firstly, it saves time in

electricity production estimation but estimation is very sensitive to time intervals of the chosen $v-i$ characteristic parameters and it always results in larger errors and value deviations with respect to emulation. Secondly, the analytical method can be used as a good check point for emulated results.

The analytical method was carried out for PANASONIC modules. In addition to values that are necessary for emulation, it is additionally required to know DC power (P_{DC}). DC power is obtained by the expression:

$$P_{DC} = (U_{MPP1} \cdot I_{MPP}) + (U_{MPP2} \cdot I_{MPP}) [kW], \quad (10)$$

where: U_{MPP1} and U_{MPP2} – string voltages at MPP, I_{MPP} – string currents at MPP.

AC power P_{AC} is then calculated as:

$$P_{AC} = P_{DC} \cdot \eta [W] \quad (11)$$

$$W = \frac{P_{AC}}{1000} \cdot (t_2 - t_1) [kWh], \quad (12)$$

where t_1 and t_2 are instants of time for two chosen input data.

A relative difference between electricity production given by analytical calculation and emulation ΔW is about 2%. This difference is obtained as the ratio of emulated (23.11kWh) and calculated (23.58kWh) electricity production:

$$\Delta W = \frac{W_{AN.} - W_{EMU.}}{W_{AN.}} \cdot 100 \% \quad (13)$$

$$\Delta W = \frac{23,58 - 23,11}{23.58} \cdot 100 \% = 1.99 \%$$

where: $W_{AN.}$ – electricity production given by analytical calculation, $W_{EMU.}$ – electricity production given by emulation.

Inverter type	Serial number	RS485 address	IP address	Yield[kWh]													
Powador 12.0 TL3	12.0TL01339150	1	0.0.0.0	23.11													
Time	Udc1[V]	Idc1[A]	Pdc1[W]	Udc2[V]	Idc2[A]	Pdc2[W]	Uac1[V]	Iac1[A]	Uac2[V]	Iac2[A]	Uac3[V]	Iac3[A]	Pdc[W]	Pac[W]	Tsyst[°C]		
6:55:06	404.1	0.06	24	436.9	0.14	65	237.2	0.8	236.6	0.82	236	0.8	90	88	33.9		
7:10:21	403.8	0.05	22	435.4	0.15	67	236.2	0.8	236.7	0.82	235.3	0.81	89	88	35.3		
7:25:36	403.5	0.22	91	400.9	0.32	129	235.7	0.86	235.8	0.87	235.4	0.85	220	215	36.4		
7:40:50	403.6	0.33	134	387.6	0.43	166	235.3	0.89	235.4	0.91	235.2	0.89	301	296	37.2		
7:56:05	403.6	0.32	133	387.7	0.43	166	234.8	0.89	234.8	0.9	234.7	0.89	299	296	37.8		
8:11:19	403.6	0.33	134	387.2	0.43	166	235.4	0.89	234.1	0.9	233.9	0.89	300	296	38.3		
8:26:34	401.1	0.32	128	388.7	0.4	158	236.9	0.88	231.1	0.9	235	0.89	287	280	38.7		
8:41:48	492.1	1.65	812	499.1	1.76	880	235.5	2.34	231.3	2.39	235.4	2.34	1695	1661	39.2		
8:57:03	502.5	1.68	845	521.7	1.79	934	236.4	2.47	231.6	2.52	235.5	2.48	1780	1759	39.9		
9:12:17	501.9	1.69	848	520	1.8	937	236.7	2.48	231.7	2.53	234.3	2.5	1788	1763	40.6		
9:27:32	497	1.22	606	526.6	1.29	681	236	1.78	231.9	1.81	234.3	1.79	1289	1264	41.2		
9:42:46	492.7	1.13	557	514.3	1.3	671	236.8	1.9	232.2	1.91	235.1	1.9	1229	1216	41.5		
9:58:01	491.9	1.15	570	512.6	1.28	657	237.6	1.69	232.4	1.73	235.5	1.71	1229	1213	41.8		

Fig. 8. Data emulated from the inverter

PAN _{ST1}	PAN _{ST2}	No.par	U _{STR1}	U _{STR2}	I _{STR}	U _{MPP,ST1}	U _{MPP,ST2}	I _{MPP,STR}	P _{Cal}	P _{DC}	P _{AC}	η	W	η _{mod}
[n]	[n]	[m]	[V]	[V]	[A]	[V]	[V]	[A]	[kW]	[kW]	[kW]		[kWh]	[%]
13	12	2	581.1	536.4	1.440	453.7	418.8	0.144	0.13	0.13	0.12	0.987	0.099	15.33
13	12	2	613.6	566.4	0.380	500.5	462.0	0.338	0.33	0.33	0.32	0.987	0.380	36.86
13	12	2	390	360	1.250	543.4	501.6	1.746	1.82	1.82	1.80	0.987	1.501	41.35
13	12	2	643.5	594	1.366	538.2	496.8	1.212	1.25	1.25	1.24	0.987	1.362	28.84
13	12	2	660.4	609.6	2.546	640.9	591.6	2.350	2.90	2.90	2.86	0.987	2.525	38.29
13	12	2	650	600	2.058	543.4	501.6	1.912	2.00	2.00	1.97	0.987	2.038	28.81
13	12	2	652.6	602.4	2.534	548.6	506.4	2.296	2.42	2.42	2.39	0.987	2.311	38.42
13	12	2	660.4	609.6	3.852	551.2	508.8	3.818	4.05	4.05	3.99	0.987	4.261	39.38
13	12	2	655.2	604.8	4.310	535.6	494.4	3.600	3.71	3.71	3.66	0.987	3.660	18.5
13	12	2	245.7	226.8	2.440	522.6	482.4	2.080	2.09	2.09	2.06	0.987	2.132	13.59
13	12	2	646.1	596.4	1.600	614.9	567.6	1.380	1.63	1.63	1.61	0.987	1.557	30.45
13	12	2	647.4	597.6	2.020	543.4	501.6	1.700	1.78	1.78	1.75	0.987	1.753	28.18
									24.1	24.1	23.8	0.99	23.58	29.83

Fig. 9. Analytical data for chosen PV system emulation

Both groups of data are in Fig. 8. and Fig. 9., respectively.

5. CONCLUSION

An advantage of this kind of a photovoltaic emulator in assessing electrical production from photovoltaic systems based on different PV modules is reflected in the following:

- a photovoltaic emulator requires much less space than a photovoltaic system,
- independence of solar irradiance, i.e., time of the day,
- a possibility to emulate PV systems with various technologies of a photovoltaic module,
- built-in protection for measurements, protecting the equipment as well as the operator,
- calibration of other devices.

Emulation of the photovoltaic system with peak power of up to 12 kW is obtained based on the measurement of the photovoltaic module PANASONIC VBHN240SE10 $v-i$ characteristics for one chosen day in the month. These data can be used for studying an optimal photovoltaic system regarding regional climatic elements.

6. REFERENCES

- [1] S. Kumari, Ch. S. Babu, "Mathematical Modeling and Simulation of Photovoltaic Cell using Matlab-Simulink Environment", *International Journal of Electrical and Computer Engineering*, Vol. 2, No. 1, pp. 26–34, 2012.
- [2] Magna-Power, "Programmable DC Power Supplies"; <http://www.magna-power.com/products>, (accessed: 12 August 2014)
- [3] Chroma- System, "Solar-Photovoltaic Array Analysis", <http://www.chromausa.com/applications/solar.php>; (accessed: 12 August 2014)
- [4] ET-System DC Sources, "PV Simulator Option", *Technical Handbook*; <http://www.et-system.de/en/applications/dc-sources.html>, (accessed: 12 August 2014)
- [5] H. Can, "Model of a Photovoltaic Panel Emulator in MATLAB-Simulink", *Turkish Journal of Electrical Engineering & Computer Sciences*, Vol. 21, No. 2, pp. 301-308, 2013.
- [6] H. Belmili, M. Haddadi, S.M. Aitcheikh, A. Chikouche, "Semi-Virtual Laboratory Design for Photovoltaic Generator Characterization Performance", *World Renewable Energy Congress*, Linköping, Sweden, 8-13 May 2011, pp. 2930-2937.
- [7] Typhoon Hill, "Hill400 Brochure"; http://issuu.com/typhoon-hil/docs/hil400_brochure?e=6302905/1103261, (accessed: 12 August 2014)
- [8] Photovoltaic Systems as Actuators of Regional Development, Database of v-i characteristics; <http://www.regphosys.eu/hr/node/90/1910>, (accessed: 12 August 2014)
- [9] I. Feher, D. Pelin, "Technical Instructions, Testing and Installation of the DC Programmable source LAB/HP 101000 produced by ET SYSTEM", 2014; <http://regphosys.eu/en/filebrowser/download/1812>, (accessed: 12 August 2014)
- [10] PANASONIC VBHN240SE10; Data Sheet for High Efficiency PV Module; http://de.krannich-solar.com/fileadmin/content/data_sheets/solar_modules/Panasonic_N235-240_VBHN2xxSE10_EN.pdf, (accessed: 17 August 2014)
- [11] D. Pelin, D. Šljivac, D. Topić, V. Varju, "Regional Impacts of Different Photovoltaic Systems", *IDResearch kft./Publikon Kiado Pecs, Pecs, Hungary*, 2014.