

PV Emulation by using DC Programmable Sources

Original Scientific Paper

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Abstract – *The paper describes fast emulation of one selected photovoltaic system. This type of emulation reduces emulation time multiple times regarding standard emulation. By speeding up emulation time it is possible to predict electricity generation in advance on a daily basis. This facilitates the evaluation and comparison of electricity generation of photovoltaic systems of different power and/or different photovoltaic (PV) modules. The emulated electrical energy of the selected photovoltaic systems will make it possible to put forward recommendations concerning the choice of the optimal photovoltaic system with regard to the climate elements of the region.*

Keywords – *DC programmable sources, emulated electrical energy, fast emulation, operational scripts, PV emulator.*

1. INTRODUCTION

According to the annual report on renewable energy sources, 227 GW of photovoltaic systems were installed in 2015. During the last 5 years, there has been a steady increase in the capacity of the installed PV systems on a yearly basis by 30-50 GW [1]. This trend is mainly a result of the price drop in the PV module construction technology, and partly due to the cost of electronic devices [2], mostly of the power electronics converter. To test electronic equipment connecting PV modules and the AC network, i.e. inverters, as well as to research electricity generation compared to different PV module construction technologies, it is necessary to come up with systems that will not depend on daily solar power and the available free surface at the top of buildings. Such systems were named photovoltaic emulators (a PV emulator). There are several different concepts of a PV emulator. One of those is aimed at mathematical modeling of a PV module. Then by using simulation tools like MATLAB or Labview, these data are used as input data for developed hardware [3-5]. It is typical for this approach that physical quantities - currents

and voltages - are scaled to quantities that are safe for handling and accessible for low cost measurements [6-8]. In this way, emulation of different PV modules was done, but there was lack of papers for obtaining emulation of a photovoltaic system in order to predict electricity generation. Therefore, in this paper, we propose an energy-based concept, where instead of scaling currents and voltages, real v-i string and/or module characteristic voltage and current values are downloaded from the database and photovoltaic modules are replaced by programmable DC sources. There are many manufacturers on the market that design programmable sources [9-11]; what all of them have in common is that they generate current and voltage characteristics of the modules based on the input characteristic values of voltages and currents for the modules. Then, programmable DC sources supply the PV grid-connected inverter and it is possible to predict electricity generation by emulation.

Such PV emulator [12], described in this paper, is used to emulate electrical energy for the systems of different power (Fig. 1).

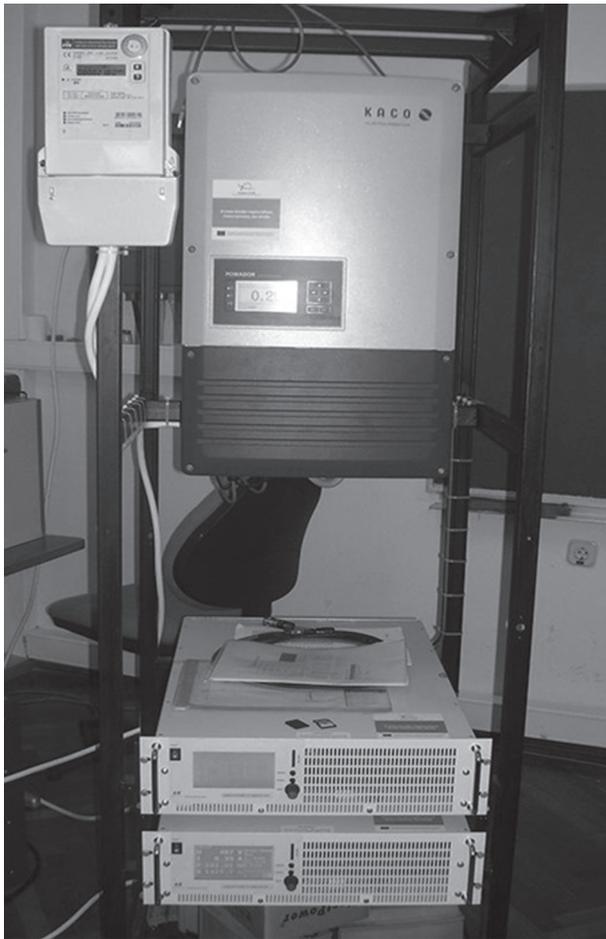


Fig 1. PV emulator

A requirement for obtaining PV emulation is an existing database containing $v-i$ characteristics of photovoltaic modules. Alternatively, string characteristic data can also be taken from the inverter of an actual PV system.

Emulation is obtained based on the input $v-i$ characteristics of modules or strings on a minute base, and as such, it is demanding and time-consuming, taking up approximately one day per emulation with all the input data. This manual entry of data at predefined time instances can lead to errors. Emulation is conducted for over 13 hours daily, which is typical duration of the daily power diagram on a spring/summer day.

Fast emulation is recommended in this paper because it enables evaluation of electricity generation of the photovoltaic system with significantly reduced emulation time on a daily basis. Emulation time reduction is enabled by using operational scripts for programmable sources [6], whereby the input of characteristic values of current and voltage is automatic and simultaneous for all DC programmable sources of the PV emulator.

Fast emulation was performed with the data obtained from the solar power plant (ETFOS1- 10kWp) inverter, whereby the emulated electrical energy was compared to electricity generation of the solar power plant. It was shown that fast emulation can be used to estimate the production of various PV systems on days with or without a significant change in solar irradiation.

The relevance of PV emulation as well as a short review of the state-of-the-art is given in the introduction. In Section 2, technical characteristics of the laboratory PV-emulator are introduced. Limitations by obtaining PV emulation with chosen laboratory set-up are highlighted in Section 3. Fast PV emulation is applied on one chosen photovoltaic system, which is described in Section 4. Finally, the conclusions of the proposed fast emulation are given in the last section.

2. PV EMULATOR

A PV emulator includes two programmable DC sources LAB/HP 101000 [13], an inverter, a junction box with protective devices, an electronic digital watt-hour meter and a metal case that holds all subsystems of the PV emulator and the connecting cable lines.

2.1. PROGRAMMABLE DC SOURCES

Programmable DC sources emulate the characteristics of PV strings. Table 1 shows the basic technical information for a programmable source.

Table 1. Technical characteristics of LAB/HP 101000

Technical characteristic	
Maximum source voltage	1000 V
Maximum source current	10 A
Connection to AC network	three-phase
Input frequency	47-63 Hz
Input voltage range	230VAC / 3x208VAC / 3x480 VAC +- 10%

Programmable DC sources can be connected into parallel or series circuits, i.e. master-slave mode, which expands voltage or current ranges of the source. There are five possible modes of operation that are shown in Table 2. To emulate PV systems, PVsim mode of operation is used.

Table 2. Modes of operation of DC sources

Mode of operation	Characteristics of the mode of operation
UI	voltage and current limit
UIP	voltage and current limit according to set power
UIR	voltage and current limit with simulated internal alternating resistance
PVsim	simulation of a photovoltaic characteristic
Script	control using a memory card

2.2. INVERTER

A photovoltaic inverter [14] is used for connecting and adjusting the characteristics of programmable sources and the power distribution network. Thereby alternating AC distribution is used as an intermediary for inverter protection which is connected to the dis-

tribution network. The inverter has two inputs, i.e. two input ports for maximum string power point tracking (MPPT). Two programmable sources that emulate photovoltaic modules can be connected to each of the input ports. One programmable source will be connected to one port for fast emulation. The inverter also has a saving function of the input and output data in a 1-30 minute time interval. All saved data can be downloaded to a computer using a USB drive for further analysis.

2.3. DIGITAL WATT-HOUR METER

To determine the emulated power, a digital watt-hour meter [15] was connected to the inverter end. Meter resolution is up to 0.01 kWh, i.e. 10 Wh, which makes it possible to determine even the atypically low values in the production of PV systems, which will also ensure evaluation of fast emulation. The subsystem connection scheme is shown in Fig. 2.

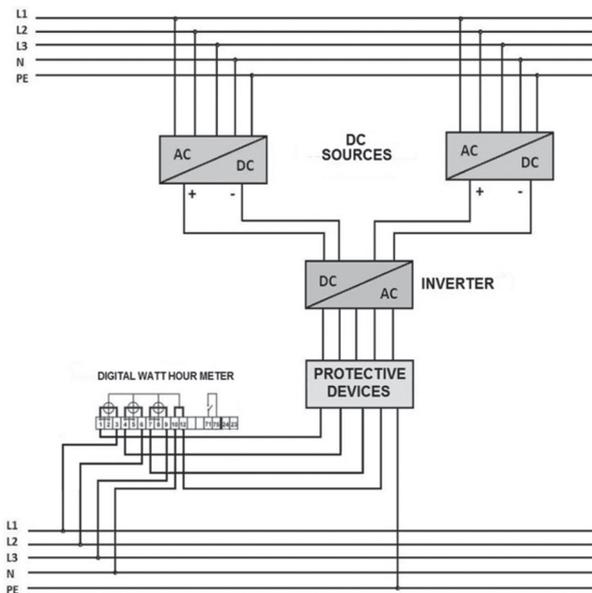


Fig 2. Schematic connection of PV subsystems

3. LIMITATIONS OF A PV EMULATOR

Smart-fast emulation proposed for PV system emulation uses a script that recalls the Pvsim mode of operation within the source code and controls the operation of programmable sources with a memory card. In predetermined moments, using the predefined commands, the requested $v-i$ characteristics are placed on both programmable DC sources. The source code was compiled in Notepad, a textual file program for MS Windows OS, Fig. 3. Such file is saved on the memory card (SD-card) and managed in an appropriate interface by a programmable source.

There are limitations when writing a script such as the maximum number of commands in a script and the limitation of the maximum allowed time interval of a certain script command. These limitations were determined by the manufacturer and cannot be altered by the user.

3.1. THE MAXIMUM NUMBER OF SCRIPT COMMANDS

By increasing the commands step by step, the testing of the maximum number of script commands has proved that the maximum number of commands that can be run with the DC programmable source LAB/HP 101000 is 35 [16]. When using the Pvsim mode of operation, a command contains 7 lines of code, i.e. 7 data items about the $v-i$ characteristic of the module or string, as shown in Fig 3. If the command number exceeds the maximum 35, upon completion of the script test, the DC programmable source will display the following notification: "Too many commands!" and the script will therefore not be completed.

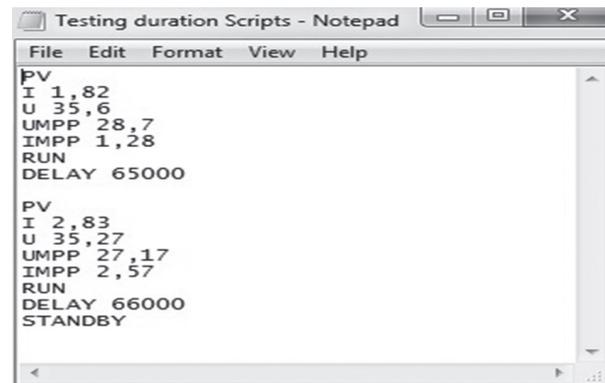


Fig. 3. An example of script command number testing and duration of a single command

3.2. THE MAXIMUM TIME INTERVAL OF SCRIPT COMMANDS

Testing the script by changing the time instance of a command (the predefined subcommand "Delay") has determined the maximum time interval of a command to be 65,000 ms or 1 minute [16]. If the subcommand is changed to a time interval longer than 65,000 ms, the source self-resets to default settings, as it continues to execute commands at a significantly shorter command time interval compared to the maximum duration of a command.

4. FAST PV EMULATION

To perform fast PV simulation of a selected PV system, a ready-made measurable database of the $v-i$ characteristics of PV modules and/or strings is required. During the project [17], a solar power plant ETFOS1 was built, which consists of two strings, each containing 20 photovoltaic modules of polycrystalline and monocrystalline module technology: BISOL BMU-250 and BISOL BMO-250. Furthermore, a database of the measured $v-i$ characteristics of PV modules was set up [18]. Using the data from ETFOS1 photovoltaic inverter (the same inverter type of the PV emulator), as well as data from the database, the entry data of the $v-i$ string characteristics was prepared for input into the DC programmable sources:

I_{mppn} - current at the maximum power point of the n -string;

V_{mppn} - voltage at the maximum power point of the n -string;

V_{ocm} - voltage of open circuit voltage of the m -technology string; and

I_{scm} - short circuit power of the m -technology string.

Electricity generation on a selected day W_{tot} (kWh) was additionally taken from the inverter. The data was collected in a 5-minute interval for 3 days without a noticeable change in solar irradiation (i.e. a so-called sunny day): 2, 3 and 12 November 2014, together with additional 3 days with a significant solar irradiation change (i.e. a so-called cloudy day): 19 April and 12 and 25 May 2016. This ensured around 130 v - i characteristics for a single emulation. The daily power diagram (power at the inverter end P_{ac} (W)) for a selected sunny and cloudy day is shown in Figures 4 and 5, respectively. The figures also show part of the file taken from the power plant inverter with the characteristic electrical energy, W_{tot} .

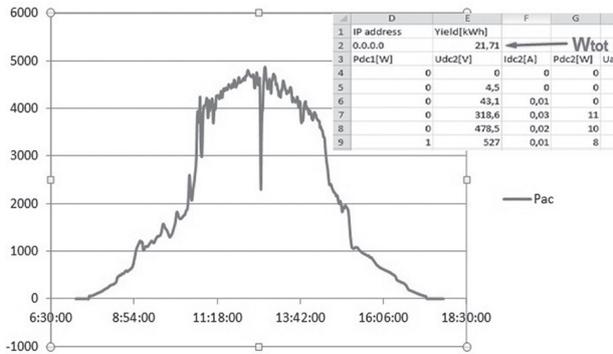


Fig. 4. Daily generated power from the power plant ETFOS1 for a sunny day (2 November 2014)

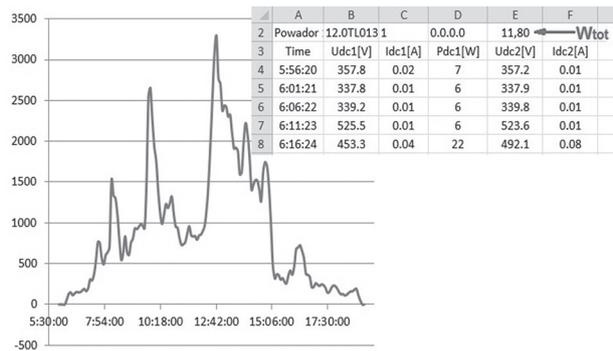


Fig. 5. Daily generated power from the power plant ETFOS1 for a cloudy day (19 April 2016)

Since the maximum number of v - i characteristics that can be used for operational scripts is limited to 35, a fast emulation table with 20 items of string characteristics was selected out of the starting table with 130 v - i characteristics (V_{mppn} , I_{mppn}), with a data time interval of 30 minutes. Table 3 was set up for writing a code for a sunny day (2 November 2014), with the initial limitation taken into account.

Table 3. Characteristic values of the power plant ETFOS1 for a sunny day (2 November 2014)

Time; t_j	V_{MPP1j} [V]	I_{MPP1j} [A]	V_{MPP2j} [V]	I_{MPP2j} [A]	P_{ACj} [W]	W_{anj} [kWh]
7:45:33	429.4	0.09	225.9	0.23	89.2	0.045
8:15:29	429.4	0.4	225.9	0.55	291	0.146
8:45:27	618.8	0.68	225.9	0.85	603	0.301
9:15:23	618.1	0.83	632.6	0.93	1084	0.542
9:45:21	615.5	1.21	629.5	1.31	1544	0.772
10:15:16	613.7	1.3	617.1	1.46	1672	0.836
10:45:12	621.5	3	635.3	3.14	3798	1.899
11:15:10	609.7	3.27	614.4	3.36	3993	1.997
11:45:06	593.1	3.73	600.3	3.84	4445	2.223
12:15:04	583.1	3.94	591	4.12	4657	2.328
12:45:00	585.6	3.77	595.8	3.8	4400	2.2
13:15:06	584.8	3.8	592.6	3.91	4467	2.233
13:45:01	586.5	3.25	594.8	3.34	3830	1.915
14:15:00	585.7	3.2	607	3.14	3720	1.86
14:45:57	592.5	2.74	646.3	0.88	2157	1.079
15:15:56	651.5	0.78	610.8	0.92	1053	0.526
15:45:51	601.4	0.67	606.6	0.76	850	0.425
16:15:49	575.8	0.43	579.4	0.54	552	0.276
16:45:45	429.4	0.23	446.9	0.39	269	0.134
17:15:43	429.4	0	225.8	0.28	62.2	0.031
					W_{an}	21,77

Based on the current and voltage data at maximum power points, Table 3, and the inverter efficiency rate = 98.4 % [8], the following is obtained:

$P_{tot,DCj}$ - DC power of both strings at the instance of time j ;

P_{ACj} - AC power at inverter output at the instance of time j ;

W_{ANj} - the obtained energy production at the instance of time j .

The expressions used for obtaining data are listed in Table 3.

$$P_{tot,DCj} = P_{MPP1j} + P_{MPP2j} = V_{MPP1j} \cdot I_{MPP1j} + V_{MPP2j} \cdot I_{MPP2j} \quad (1)$$

$$P_{ACj} = \eta \cdot P_{tot,DCj} \quad (2)$$

$$W_{anj} = \frac{(P_{ACj}) \cdot (t_{j+1} - t_j)}{1000} \quad (3)$$

where t_j is the selected instance of time for the j -characteristic.

W_{an} , the obtained energy production for the selected day, is taken from the expression:

$$W_{an} = \sum_{j=1}^N W_{anj} \quad (4)$$

The obtained energy production, W_{an} , for all 6 days is listed in Table 4, together with the total electricity generation, W_{tot} and the relative error, δ .

Table 4. Generated electricity of the power plant ETFOS1

Date	Sunny day			Cloudy day		
	2 Nov	3 Nov	12 Nov	12 May	19 Apr	25 Feb
W_{tot} [kWh]	21.71	23.36	34	14.5	11.8	11.56
W_{an} [kWh]	21.77	23.76	33.73	15.73	12.49	11.18
δ [%]	-0.3	-1.7	+0.79	+8.4	-5.9	-2.7

Due to the limited number of script commands, there is no significant deviation between the total electricity generation W_{tot} and the obtained energy production W_{an} for sunny days (relative error less than 2%), whereas a more notable deviation is characteristic of cloudy days. This makes sense considering a sudden change in solar irradiation, which matches a sudden change in power in the daily diagram (Fig. 5). The relative error, however, is lower than 10% for the selected days. Additionally, the deviation on cloudy days is both positive and negative in nature, which will result in a smaller total error when obtaining the measured emulated energy of the PV system on a monthly basis. Therefore, the total electricity generation, W_{tot} will be used as a starting point for comparison, for emulations of the sunny days, and the obtained energy production, W_{an} will be used for cloudy days.

The other limitation when writing the script takes into account the time interval of a single v-i characteristic, i.e. a maximum of 1 minute. Since the characteristics in the starting table are based on a 30-minute sample, time-scaling was conducted so that each command takes 1 minute, and upon completion of emulation the obtained emulated energy for an instance of time j , $W_{em,anj}$ (kWh) is recalculated for a 30-minute emulation, using the following expression:

$$W_{em,anj} = \sum_{n=1}^2 U_{MPPTnj} \cdot I_{MPPTnj} \cdot \frac{\Delta t_j \cdot 30}{1000 \cdot 60} \cdot \eta \quad (5)$$

where Δt_j is the emulation interval of 1 minute.

The obtained emulated energy $W_{em,an}$ is given as follows:

$$W_{em,an} = \sum_{j=1}^N W_{em,anj} \quad (6)$$

Table 5 lists string currents and voltages at the maximum power point, taken from the emulator inverter upon completion of emulation. The obtained AC power is calculated by using expression 2, P_{ACj} was entered into the table, as well as the obtained emulated energy, $W_{em,an}$ according to expression 3.

Table 5. Characteristic values of emulation for a sunny day (2 November 2014)

Time; t_j	U_{mpp1j} [V]	I_{mpp1j} [A]	U_{mpp2j} [V]	I_{mpp2j} [A]	P_{ACj} [W]	$W_{em,anj}$ [kWh]
5:05:12	490	0.04	405.9	0.03	31.28	0.016
5:06:14	488	0.34	401.2	0	163.2	0.082
5:07:16	525	0.72	407.4	0.03	383.8	0.192
5:08:18	602	0.85	527.5	1.07	1059	0.53
5:09:20	616	1.2	615.9	1.41	1582	0.791
5:10:22	613	1.48	615.6	1.75	1953	0.977
5:11:24	621	3.02	631.6	3.15	3802	1.901
5:12:26	609	3.34	614.9	3.46	4095	2.048
5:13:28	590	3.74	599.3	3.93	4490	2.245
5:14:30	582	3.87	589	4.11	4598	2.299
5:15:32	584	3.75	592.2	3.88	4416	2.208
5:16:33	582	3.62	593.4	3.78	4282	2.141
5:17:35	585	3.22	596.5	3.34	3813	1.907
5:18:37	581	3.11	613.2	2.27	3149	1.574
5:19:39	600	2.02	636.9	0.82	1706	0.853
5:20:41	636	0.69	607.8	0.92	982	0.491
5:21:43	587	0.55	599.1	0.71	736	0.368
5:22:45	549	0.25	562.9	0.45	384.2	0.192
5:23:47	488	0.06	457.5	0.18	109.9	0.055
5:24:49	343	0.02	304.1	0	6.748	0.003
					$W_{em,an}$	20.87

Calculation of the obtained emulated energy $W_{em,an}$ is a revision of the measured emulated energy, $W_{em,count}$, which is also recalculated upon emulation, due to emulation time-scaling:

$$W_{em,cont} = (W_{end} - W_{start}) \cdot 30 \text{ [kWh]} \quad (7)$$

where:

W_{end} – the final watt-meter count;

W_{start} – the initial watt-meter count.

For instance, the digital watt-meter hour on a sunny day (2 November 2014) gives: $W_{start}=58.22$ kWh, $W_{end}=58.93$ kWh, which yields measured emulated energy $W_{em,count}=21.3$ kWh. The measured emulated energy $W_{em,count}$ is, therefore, the energy compared to the generated electrical energy of the solar power plant ETFOS1.

The fast emulation time instance amounts to 20 minutes, while standard emulation on a sunny day would require 9 hours and 30 minutes. The deviation is even more noticeable on spring days (19 April) when standard simulation takes more than 12 hours [19]. In this way, fast emulation significantly reduces emulation time.

Based upon a comparison of characteristic values of the data taken from the power plant inverter, Table 3 and the values taken from the inverters of the PV emulator, Table 5 reveals that for emulations corresponding to the morning and evening hours and lower amounts

of produced power (<100 Wh), the MPPT inverter system does not keep the operating point on a curve at the point of maximum power, with determined $v-i$ characteristics of DC programmable sources. This correlates to the data from technical specifications of the inverter [14]. It should, therefore, be expected that the amount of the obtained emulated energy, $W_{em'}$ will always be lower than the obtained energy production, W_{an} .

Emulation results for all 6 days are summed up in Table 6. The relative error, $\delta_{em'}$ of the measured emulated energy and the corresponding electricity generation of the power plant is derived from expressions 8 and 9 for a sunny day and a cloudy day, respectively.

Table 6. Final list of electrical energy

Date	Sunny day			Cloudy day		
	2 Nov	3 Nov	12 Nov	25 Feb	19 Apr	12 May
W_{tot} [kWh]	21.71	23.36	34	/	/	/
W_{an} [kWh]	/	/	/	11.18	12.49	15,7
$W_{em,count}$ [kWh]	21.3	23.1	33,17	10.5	11.7	14,7
δ_{ems} [%]	+1.8	+1.1	+2,4			
δ_{emc} [%]		+6	+6.3	+6.5		

$$\delta_{ems} = \frac{W_{tot} - W_{em,count}}{W_{tot}} * 100 \text{ [%]} \quad (8)$$

$$\delta_{emc} = \frac{W_{an} - W_{em,caunt}}{W_{an}} * 100 \text{ [%]} \quad (9)$$

All types of characteristic electrical energy (produced, obtained, emulated) are shown in Figure 6 for sunny days, and Figure 7 for cloudy days.

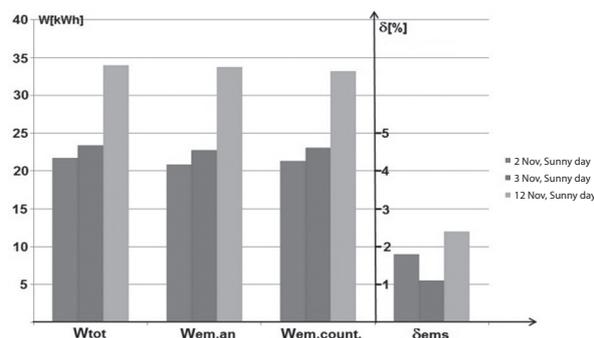


Fig. 6. Characteristic electrical energy and relative error for sunny days

Emulation errors in relation to the actual results are 3% at most for sunny days, whereas the deviations on cloudy days are a bit more noticeable, although still lower than 7%. This points to the fact that the purpose of fast emulation is to estimate energy production of PV systems of different power outputs and/or different

technologies of photovoltaic modules, as well as a daily and a monthly basis, due to different modes of the relative error, in case there is already a database of $v-i$ characteristics of the module.

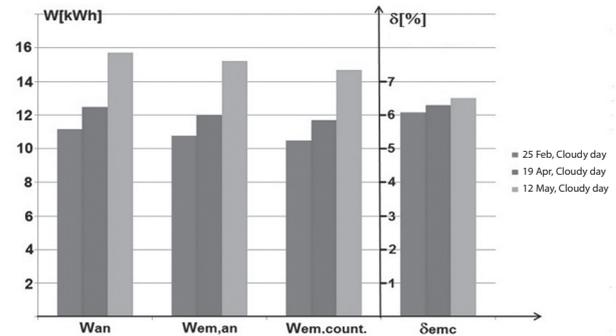


Fig. 7. Characteristic electrical energy and relative error for cloudy days

5. CONCLUSION

Fast emulation was obtained for 6 days, with and without a noticeable change in solar irradiation, for the solar power plant ETFOS1, which consists of two strings, each containing 20 PV modules of polycrystalline and crystalline production technology, and by using $v-i$ characteristics of modules from database.

The fast emulation time instance was shortened from 9.5 hours, which is standard emulation duration, to 20 minutes for a selected winter day with no significant change in solar irradiation. In this case, there is a relative error between the measured emulated electrical power and the produced power at ETFOS1, which amounts to 1.8 %. This indicates that usage of fast emulation for estimating electrical energy production of different PV systems is justified regarding initial assumptions. PV systems of different power and /or technologies can thus be compared on a daily basis. The relative error for the selected days with a greater change in solar irradiation is slightly higher and amounts to 7%. However, the nature of the error sign points out the fact that fast emulation can be performed on such days as well. All this ensures requirements needed to perform fast emulation in order to estimate the production of PV systems on a monthly basis, with the aim of setting future recommendations concerning an optimal PV system, considering the technologies of PV modules for climate elements of a region.

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