

## IN-GRID SOLAR-TO-ELECTRICAL ENERGY CONVERSION SYSTEM MODELING AND TESTING

by

**Zoltan J. ČORBA\***, **Vladimir A. KATIĆ**,  
**Boris P. DUMNIĆ**, and **Dragan M. MILIĆEVIĆ**

Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia

Original scientific paper  
DOI: 10.2298/TSCI120224069C

*In this study, a simulation model of in-grid solar-to-electrical energy conversion system is presented. In this case, the in-grid solar-to-electrical energy conversion system is small photovoltaic power plant, which was constructed by the Center for Renewable Energy and Power Quality from the Faculty of Technical Sciences. Equivalent circuit diagram of photovoltaic cell is described which was used to develop the simulation model of modules. Possible types and topologies of inverters are also described. The photovoltaic power plant is described briefly, because it is necessary to understand the simulation model. The result of simulation is an electricity annual production by the power plant. These results were compared with the real values, while its get a good overlap. The paper also presents the modern modeling methods developed at Faculty of Technical Sciences in the Laboratory for RES systems.*

**Key words:** *in-grid photovoltaic systems, modeling, equivalent cell circuit diagram, inverter topology, real time simulation*

### Introduction

Renewable energy sources become a more and more important contribution to the total energy production in the world. Today the energy production from photovoltaic (PV) energy compared to the other renewable energy sources is very low, but the PV systems are one of the fastest growing in the world. Thanks to the permanent decreasing price of PV system components, especially the PV modules, market for PV is expanding rapidly. The cost of PV modules have dropped during 2011 and the end of the year reached average level of around 1 €/Wp for the mono- and polycrystalline Si. On the Chinese and Taiwan market the modules price were around 0.8€/Wp.

Photovoltaic generator (cell, module) and PV inverter are the main components of the PV systems. Apart of the main components, there are a few elements which affect the PV system performance and depend on the design quality. PV modules are generators. They act as solar-electrical energy converters with relatively low efficiency (10-20%), whose energy production is highly dependent on weather conditions, more accurate of solar radiation and ambient temperature. These variables must be taken into consideration when modeling the photovoltaic modules,

\* Corresponding author; e-mail: zobos@uns.ac.rs

optimizing and designing the PV systems. Due to the low efficiency of the PV modules, PV inverters should have a high efficiency. The power converters integrated in the PV inverters enables high efficiency over 95%, provide synchronization with the grid, detect and manage islanding conditions, enable control under grid faults, control harmonics control and control stability.

PV inverters convert DC voltage from PV modules output to AC grid compatible voltage. To enable efficient use of PV systems adequate modeling and testing is essential. The aim of this paper is to present an overall model of PV system. The model is applied to 10 kW roof-top in-grid PV system and simulation results are presented. The results are compared with actual production of a real system and tested for different weather conditions.

### Solar cell equivalent circuit

The solar cell essentially is a PN junction, as a semiconductor diode, which converts sun rays energy into electrical energy. The cell is a non-linear device and can be represented by the I-V characteristics [1], or by an approximate electrical equivalent circuit. Five basic equivalent solar cell circuit diagrams are in use: ideal model, simple model, standard model, two-diode model and effective solar cell characteristic [2]. Ideal cell model is simple for application but gives a low accuracy during the modeling. The simple model with cell internal series resistor and standard model with cell internal series resistor  $R_s$  and parallel resistor  $R_p$  provides good approximation accuracy. The best accuracy has a two-diode model and effective solar cell characteristic.

The real PV cell has serial and parallel resistance because of PN junction properties. The standard cell model with serial and parallel resistance is shown in fig. 1.

Output current of a cell is calculated as:

$$I = I_{ph} - I_d \left( e^{\frac{U + I R_s}{U_T}} - 1 \right) - \frac{U + I R_s}{R_p} \quad (1)$$

where  $U$  is the cell output voltage,  $I_{ph}$  – the cell photocurrent (light generated current),  $I_d$  – the cell reverse saturation dark current,  $U_T$  – the thermal voltage (temperature-dependent),  $R_s$  – the series resistance, and  $R_p$  – parallel resistance

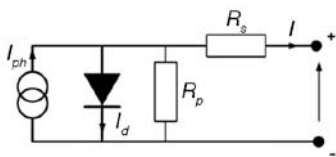


Figure.1 Standard cell model

The most important parameters which the manufacturers are given and used to describe the PV cells are short-circuit current  $I_{SC}$  and open-circuit voltage  $U_{OC}$ . The short-circuit current is obtained when the output voltage of the PV cell is equal to zero. Under normal conditions the photocurrent is much greater than cell's reverse saturation dark current, therefore the short-circuit current  $I_{SC}$  is approximately equal to the photocurrent  $I_{ph}$ . Open-circuit voltage is determined

when there is no current at the output cells. Open-circuit voltage is proportional to the natural logarithm of the relationship between of photocurrent and reverses saturation dark current.

Weather dependent production of photovoltaic modules is caused by the change of light-generated current that depends on cell temperature and solar radiation. Dependency is described by the following expression:

$$I_{ph}(G) = [I_{sc} + \alpha (T_c - T_{ref})] \frac{G}{G_0} \quad (2)$$

where  $I_{SC}$  is the cell's short circuit current at standard test conditions (STC), where cell's temperature  $25\text{ }^{\circ}\text{C}$  and solar irradiance  $1000\text{ W/m}^2$ ,  $\alpha$  – the cell's short circuit current temperature coefficient,  $T_c$  – the cell's temperature,  $T_{ref}$  – the cell's reference temperature at STC,  $G$  – the solar irradiance, and  $G_0$  – solar irradiance at STC ( $G = 1000\text{ W/m}^2$ ).

## PV module configurations

Typical photovoltaic cells voltage is about  $0.5\text{ V}$ , while the current is up to  $8\text{ A}$ . These cell values give a small power. Because of the cells low power, the serial-parallel connection must be formed by the cells. In this way forms the module, which has a much higher power. Today the PV modules manufacturers are offering modules which maximum power often amounts up to  $300\text{ W}$ . Except in very small stand alone PV systems among several of  $10\text{ W}$ - $100\text{ W}$  the modules are connected in series-parallel configuration, to ensure even greater electricity power. In the PV plants the usual modules connection is serial, called PV string (fig. 2).

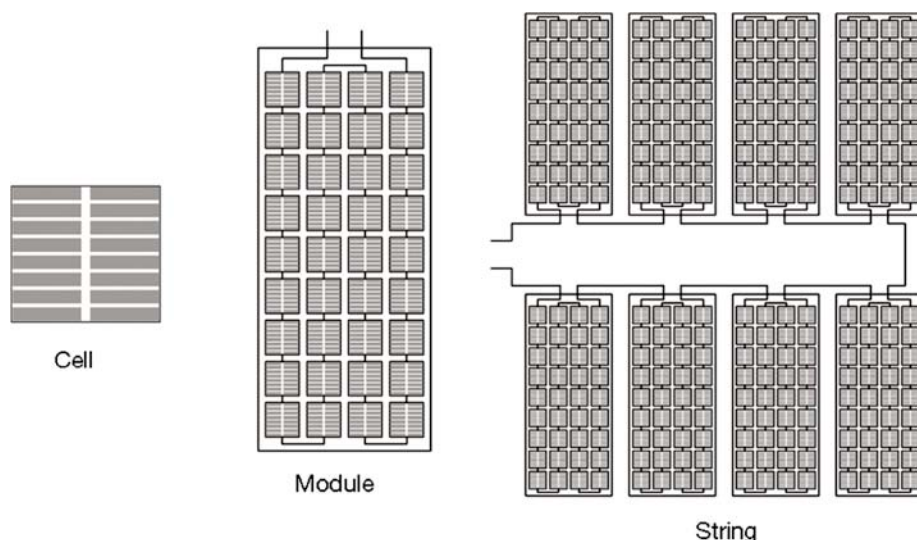


Figure 2. PV cell, module and string

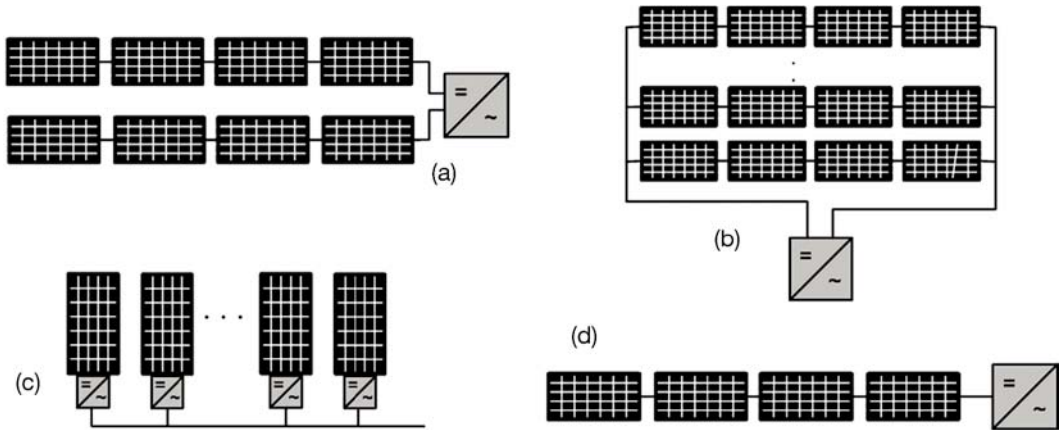
The vast majority of the PV modules are manufactured as a serial connection of PV cells. The impact of serial resistance increases and the parallel resistance can be neglected, because the cells and modules are connected serial [3]. If the  $N_s$  cells connected in series then the current expression of PV module can be written as

$$I = I_{ph} - I_d \left( e^{\frac{U/N_s + IR_s}{U_T}} - 1 \right) \quad (3)$$

## Structure of PV system

Depending on the PV plant configuration and system power level, various inverter configurations are used [4]. There are single-phase inverter for connecting photovoltaic modules to a single-phase grid or more of them to the three-phase grid and three-phase inverter for connecting to the three-phase grid. Very small PV plants use module integrated inverters, by

another name micro inverters. Single-phase string or multi-string inverters are used for small or medium roof-top PV plants. For large roof-top installation or smaller grounding mounted PV plant three-phase multi-string or mini central inverters are used. In the largest PV plants central inverters being installed. Figure 3 shows the different connecting configurations between PV modules and inverters.

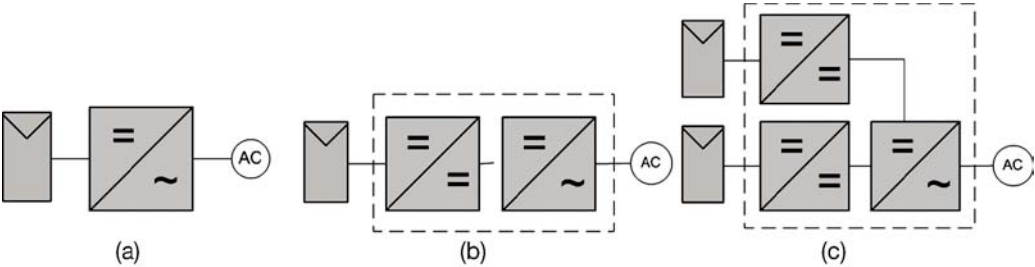


**Figure 3.** PV plant different connecting configurations; (a) Multi string inverter, (b) Central inverter, (c) Micro inverter, (d) String inverter

**PV inverter configurations**

Observing the internal inverters topology they can be divided into inverters with transformer and without them. Transformerless PV-inverters use a simple topology, with greater efficiency and they are cheaper.

The different inverter technologies also can be categorized based on the number stages of processing power [5]. Inverter with one stage of power processing or one phase inverter is shown in fig. 4(a). In one level is integrated the maximum power point tracking (MPPT), the current control and voltage amplification. This is a typical configuration for small or large scale centralized inverter. Dual-stage inverter is shown in fig. 4(b). In the DC-DC converter is implemented the MPPT and the DC-AC inverter task is convert the voltage and connect system to the grid. Inverters version with two DC-DC converter and the common inverter is called multi-string inverter which shown in fig. 4(c). The advantage of this inverter is an independent maximum power finding, which comes to expression when different strings work under different conditions.



**Figure 4.** (a) One-stage inverter, (b) Dual-stage inverter, (c) Multi-stage inverter

Each PV inverters have a DC to AC converter with transistors, regardless of the type. Transistors topology in the inverter is slightly different from the inverter, which apply in electrical drive industry. In contrast to the typical full-bridge topology, which is used in the motor drives, for needs of PV inverters a new transistors topology has been developed. New topologies allow using transformerless inverters, which increases the efficiency up to 2 percent [6].

Until now, two types of topologies were accepted by the PV inverter manufacturers:

- full-bridge or H-bridge, and
- neutral point clamped (NPC).

The basic H-bridge topology for PV inverter is shown in fig 5. Three modulation methods are used to transistor control. These are bipolar modulation, unipolar modulation and hybrid modulation.

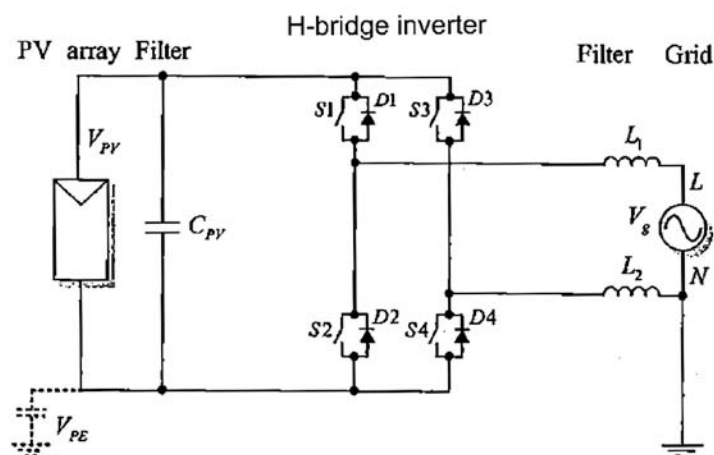


Figure 5. PV inverter basic topology

The lack of bipolar modulation is low inverter efficiency that is not greater than 96%. Unipolar and hybrid modulation are achieved higher efficiency. H-bridge topology is not suitable for transformerless inverters, regardless of the type of modulation, because of disadvantages like the reduced efficiency, the high frequency content or square wave variation of the VPE voltage (shown in fig. 5), as a result of leakage current.

The inverter manufacturers have developed improved or new transistor topology to eliminate the disadvantages of H-bridge topology. SMA solar technology manufacturer of PV inverter patented an improved H-bridge topology called H5 in 2005. The H5-topology [7] shown in fig. 6(a) only needs one more switch compared to the normal full bridge. Topology have maintained the good features of H-bridge with hybrid modulation, eliminates the high-frequency content of VPE voltage. This topology is suitable to use with transformerless inverters. This kind of inverter has high efficiency, low leakage current and EMI.

The HERIC topology, shown in figure 6(b) introduces a combination of two switches and diodes in parallel to the grid.

HERIC topology is the Sunway patent registered in 2006 [8]. The HERIC topology improves the performance of H-bridge with bipolar modulation. This topology is very suitable to use in transformerless application. PV inverters with H5 topology are slightly lower efficiency than the HERIC topology inverter. The next topologies are also developed; REFU inverter topology, full-bridge inverter with DC Bypass and full-bridge zero voltage rectifier.

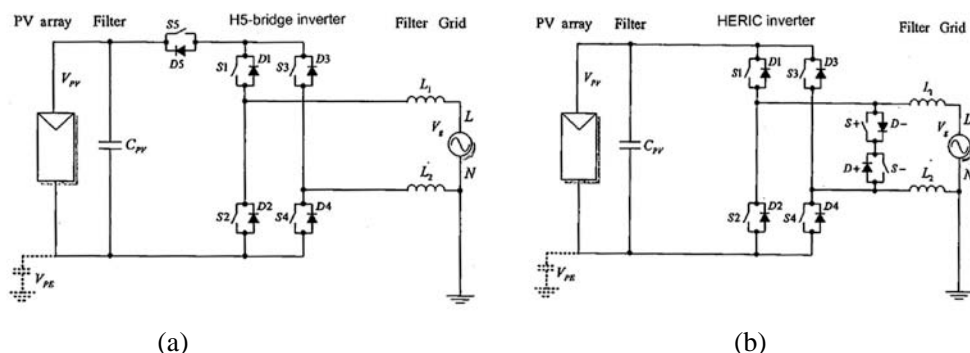


Figure 6. (a) H5-bridge inverter topology, (b) HERIC inverter topology

The other types of topologies that are different from the H-bridge topology are neutral point clamped or NPC topology. The NPC topology is very adaptable and can be used in both single-phase and three-phase inverters. The classical NPC inverter topology shows fig. 7. NPC has very similar features as H5, HERIC or REFU inverter topology and it is currently used in industrial PV inverters.

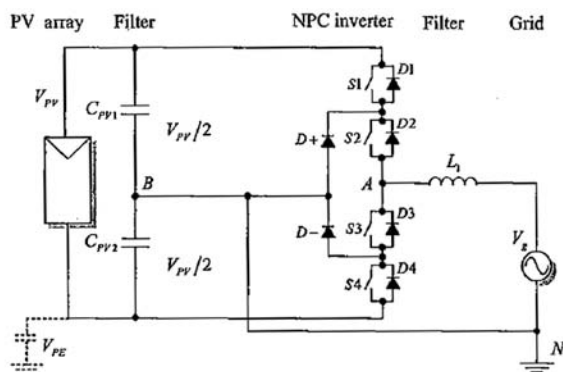


Figure 7. Neutral point clamped inverter topology

The simplest three-phase PV inverter topology is three-phase full-bridge topology. Regardless of the simplicity it is mostly used topology in practical realizations. These topology shows fig. 8. There is also a three-phase full-bridge PV inverter topology with split capacitor. This topology is equivalent to the three independent single-phase half-bridge PV inverters topology [9]. The third variant of three-phase PV inverter topology can be modularized topology, based on a three single-phase neutral-point clamped inverter.

### Photovoltaic power plant implementation

It is necessary to briefly explain the configuration of realized power plant at the Faculty of Technical Sciences (FTS), for better understanding of the simulation model which will be discussed. The PV power plant block diagram is shown in fig. 9. Photovoltaic field makes two strings of 20 panels, connected in series, with individual nominal power of 240 Wp. In the AC box are placed three-phase PV inverter and the necessary protective and switching equipment. PV inverter nominal output power is 8 kW. Inverter has two independent MPPT inputs A and B. This PV inverter used version with two DC-DC MPTT converters and the common

three-phase full-bridge transistor inverter. One PV string is connected to the input A and the other to the input B.

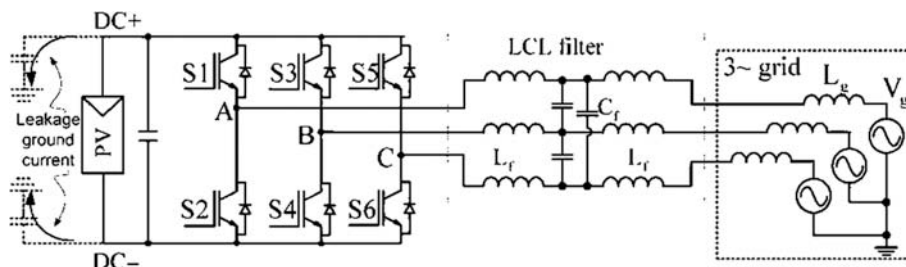


Figure 8. Three-phase full-bridge topology

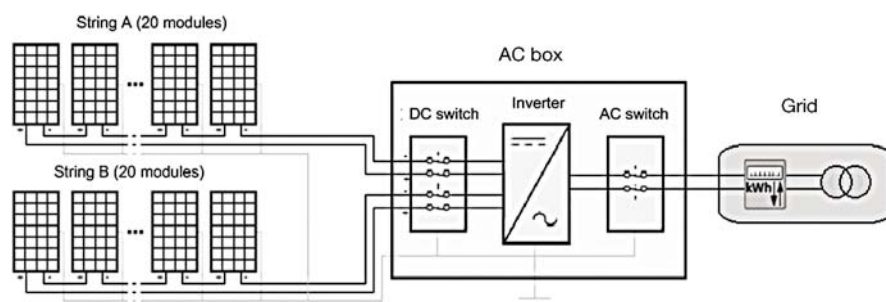


Figure 9. PV plant diagram

Figure 10 shows the AC box with SMA Tripower 8 kW inverter (left) and 2 PV strings on the flat roof of the FTS (right).

### Simulation model of photovoltaic power plant

A Matlab/Simulink software tool was used to modelling a small photovoltaic power plant which was commissioned on Faculty of Technical Sciences from Novi Sad in the end of October of 2011. Simulation result gives forecast annual production of electricity for PV system. The biggest impact on PV panel output power has a change of solar radiation and ambient temperature and in this way on the electricity production of system. Therefore, it is necessary to create a model, which can be performed simulations of PV module work, depending on the insolation and temperature.



Figure 10. Realized PV plant at Faculty of Technical Sciences

### PV module model

For the successful modeling of PV module it is necessary to take into consideration the relationship between input and output parameters of the cell. The mathematical equations that describe the equivalent circuits of PV cell are given in chapter 1. Figure 11 shows a PV module model which will be one of the subsystems in the final model. The subsystem inputs parameters are the solar radiation and module voltage. The subsystem maske of model is designed, in which the PV module parameters can be configured.

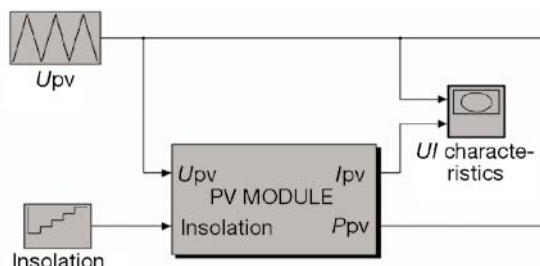


Figure 11. Photovoltaic module model

PV modules parameters which are installed at the PV plant and to be entered into the mask, at standard test conditions are:

- $I_{mpp}$  – module current at maximum power,  $I_{mpp} = 8.01$  A
- $U_{mpp}$  – module voltage at maximum power,  $U_{mpp} = 30$  V
- $I_{sc}$  – module short-circuit current,  $I_{sc} = 8.56$  A
- $U_{oc}$  – module open-circuit voltage,  $U_{oc} = 37.2$  V
- $\alpha$  – short-circuit current temperature coefficient,  $\alpha = 0.05\%/K$
- $\beta$  – open-circuit voltage temperature coefficient,  $\beta = -0.27\%/K$
- $\gamma$  – maximum power temperature coefficient,  $\gamma = 0.45\%/K$

The module U-I characteristics are shown in fig. 12, for the different radiation and cell temperature of 20 °C and 60 °C. PV module nominal power is 240 Wp.

Figure 12 shown U-P module characteristics for the same conditions which appropriate to U-I characteristics from the fig. 13.

### Model of annual power production

As mentioned, aim of the study is the assessment PV plant annual production by simulation, based on the input parameters of radiation and ambient temperature. Solar radiation and ambient temperature the surroundings of Novi Sad was determined using an interactive software PVGIS. The average daily global radiation for each month is input parameter of radiation. The PVGIS global clear-sky, global and diffuse average daily radiation is shown in fig. 14, for January and August. Radiation values are given for the inclined surface of 30 degrees. The modules at the PV plant are installed at the same inclined angle. In the model is considered that the temperature as an input parameter is the same and equal to the average daily temperature for the month, for each day during one month.

The part of model with input parameters are average daily global radiation, average daily temperature for month and number of days in month are shown in fig 15.

The final model for the assessment of electricity production of the PV plant is shown in fig. 16. Final model consists few basic blocks which are the block of input parameters A, two



block of photovoltaic arrays B1 and B2, two block of MPPT C1 and C2 and a DC to DC converter block D. A block of input parameters has been described and shown in Figure. Blocks B1 and B2 are identical and represent the PV string with 20 PV modules connected in series. Because inverter has two independent inputs, in the model is necessary to use two MPPT blocks whose outputs are connected to 2 independent DC/DC Boost converters.

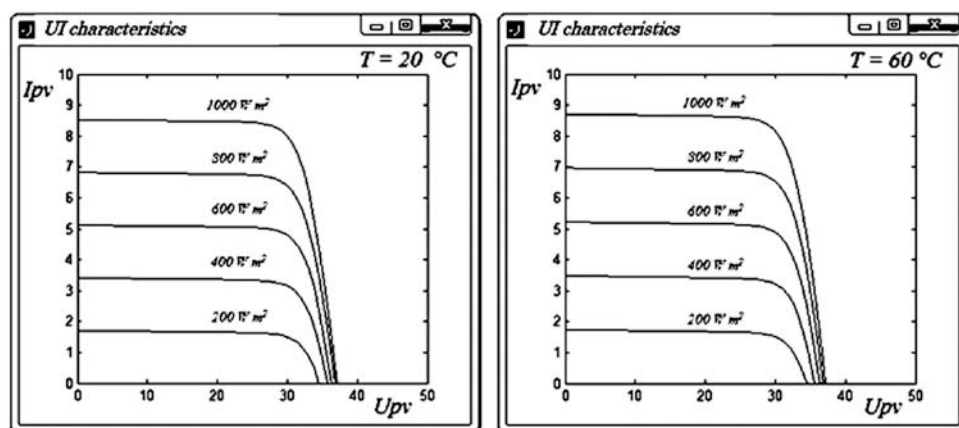


Figure 12. Modules  $U$ - $I$  characteristics

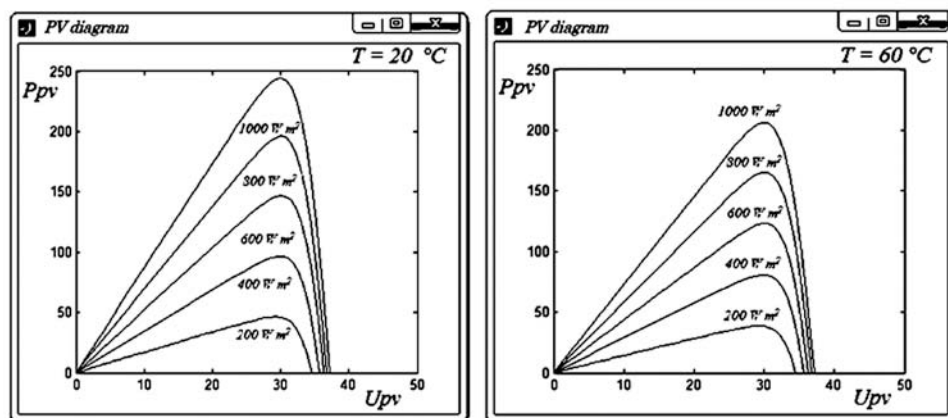


Figure 13. Modules  $P$ - $U$  characteristics

Strings output are connected to the MPPT blocks input which output is reference current, which corresponds to maximum power point. The MPPT output reference currents are conducted to the PV strings inputs in order to control operating point during the simulation. To the D block inputs are connected the reference currents from both MPPT blocks and the appropriate voltages from PV strings.

### Simulation results

The result of a simulation model is electricity energy generated per month, which is shown in fig. 17. The output values were obtained by the average daily global radiation. The sum of annual production by simulation model is 12160 kWh.

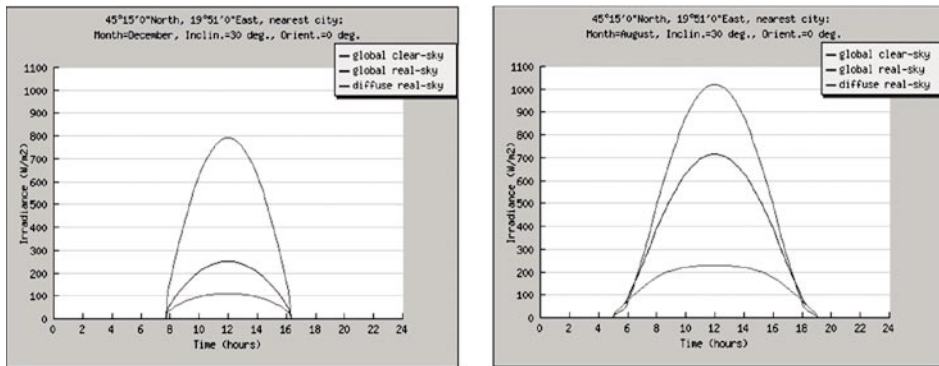


Figure 14. Global clear-sky, global and diffuse average daily radiation

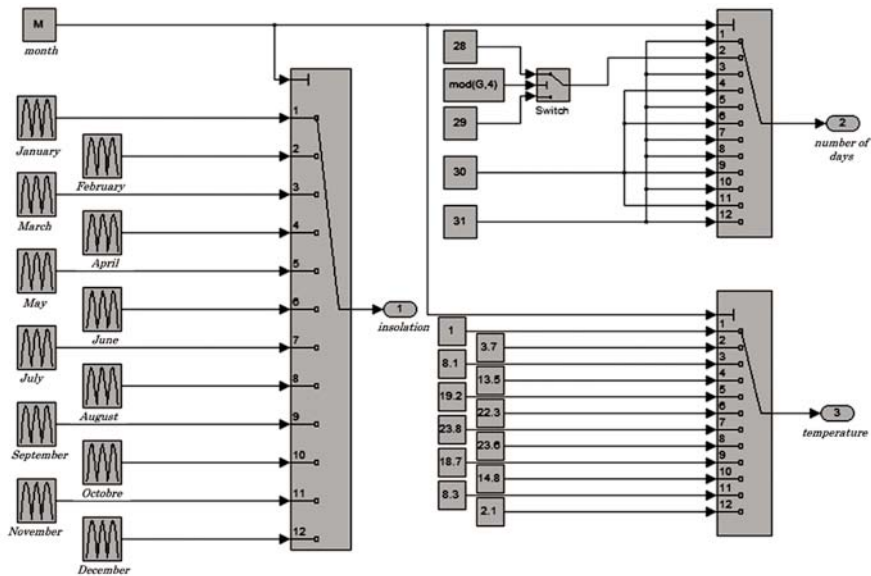


Figure 15. The models input parameters

Other than simulation of annual production, the analysis was made for a day. November's sunny day was chosen. Changes of real solar radiation for the November 18<sup>th</sup>, of 2011, are shown in fig. 18. These values of radiation are used as input parameter in the simulation model. In this way, as a result of simulation is obtained daily change of PV plant output power.

Figure 19 shows the inverter output power changes while the simulation model input parameter is real daily radiation change.

The actual change of plant output power, during the day is shown in fig. 20. The rapid growth power is observed on the ascending part of curve, in the early morning. This is a consequence of the shadows termination on the one PV string, which model is not observed.

### Comparison with actual results

Comparison of simulation results and the PV plant actual production is possible for three months, because the plant is commissioned at the end of October 2011<sup>th</sup>. This comparison

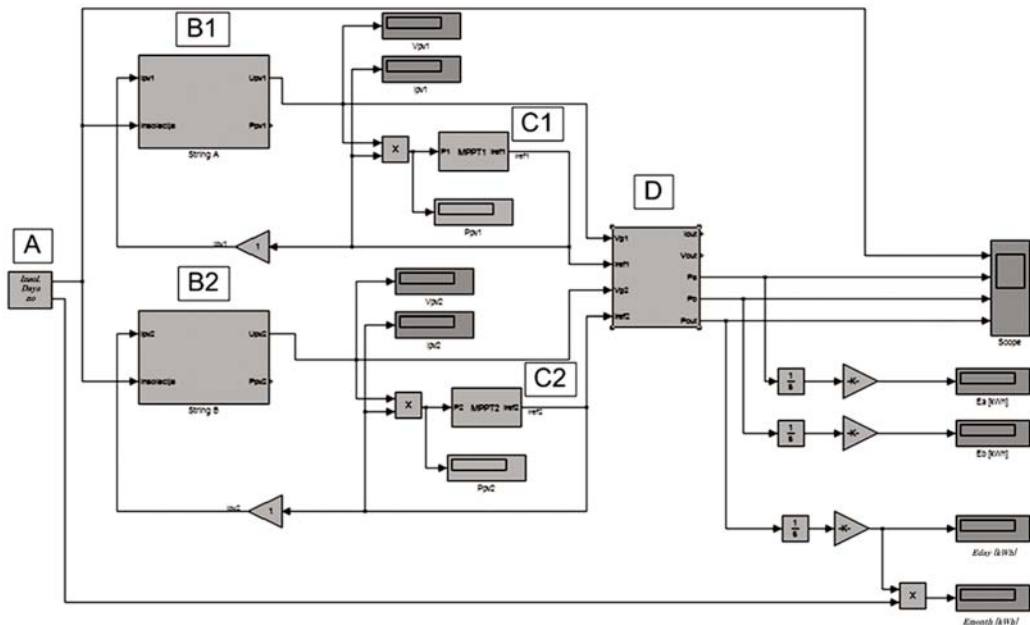
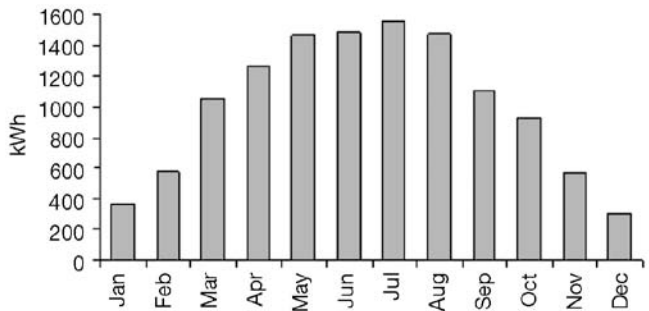


Figure 16. The realized PV plant model

Figure 17. Monthly energy production by simulation



is presented in fig. 21. The time interval of three months is very short for a good assessment of the validity of the simulation. Also should not be forgotten, that the simulation results obtained by the ten-years average values of input parameters. In November, by the results of the simulation, production was higher for 15kWh than to the actual production. The PV plant electricity production is slightly higher than the results of simulation in December and January. For these two months the average difference is 30 kWh, which is equal with the average production during a one sunny day in January.

The real and simulation based cumulative production is shown in fig. 22. Cumulative production is shown for the first three months of plant operation. The actual production is higher by 130kWh at the end of the third month of plant operation.

Fig. 23 shows the comparison between simulation result and electricity production obtained using PVGIS. In months with more clouds PVGIS gives somewhat higher values when the average cloudiness lowers, values of the simulation models are greater. Results of these differences are that the sum of annual production by PVGIS is 11400kWh and by simula-

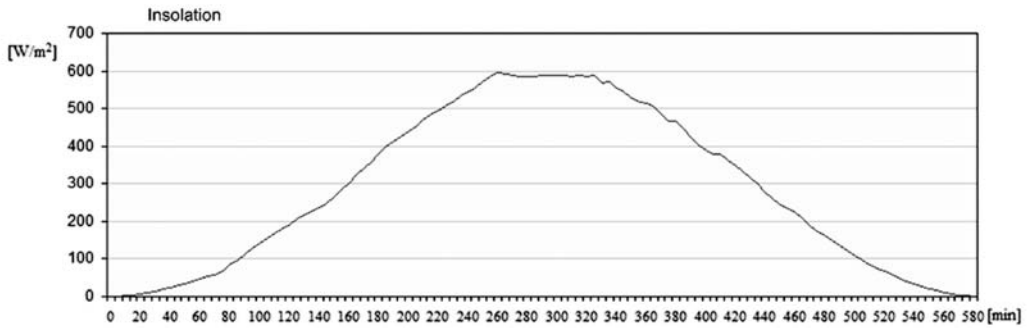


Figure 18. The real solar radiation and inverter real output power

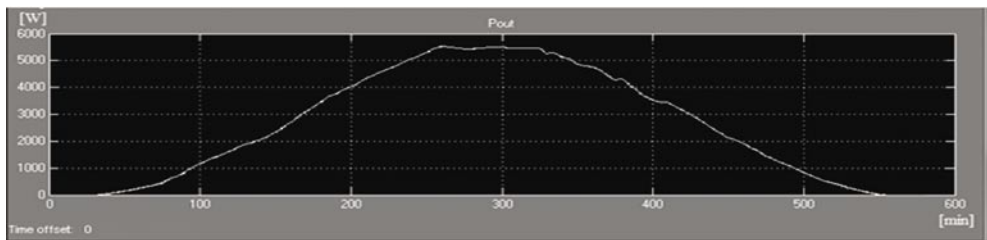


Figure 19. The inverter simulated output power

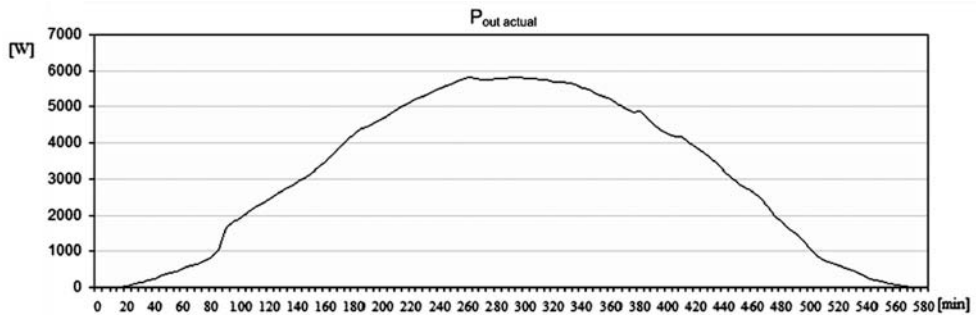


Figure 20. Actual changes of PV plant output power

tion model is 12160kWh. Difference of 6% is caused by various handling of the temperature values during the simulation and use of PVGIS. For each day, a simulation model using the average daily temperature for the considered month is applied. PVGIS is used from its database the temperature change during the day, which depending on the radiation.

## Conclusions

Installed PV power plant at the Faculty of Technical Sciences enables the validation of simulation methods. On the other hand, various simulation methods could help to optimize PV system. Detailed analysis of PV plant operation and comparison with simulation model will be possible to make after a longer period of exploitation. The further improvement of the simulation model will allow the less output errors. The better prediction of PV plant production can be enabled by entering accurate input parameters. Integration of input parameters, like ambient temperature

and solar radiation, based on the meteorological forecasts will allow the prediction of PV plant production for the next few hours or days.

## References

- [1] Guney, I., Onatte, N., Technological status and market trends of photovoltaic cell industry, *WSEAS Transactions on Electronics*, 5 (2008), 7, pp. 303-312
- [2] Wagner, A., Peak-power and internal series resistance measurement under natural ambient conditions, *Proceedings EuroSun 2000*, Copenhagen, 2000
- [3] Huan-Liang, T., Ci-Siang, T., Yi-Jie, S., Development of Generalized Photovoltaic Model using MATLAB/SIMULINK, *Proceedings WCECS 2008*, San Francisco, Call., USA
- [4] Schimpf, F., Norum, E., Grid connected Converters for Photovoltaic, State of the Art, Ideas for Improvement of Transformerless Inverters, NORPIE/2008, Nordic Workshop on Power and Industrial Electronics, 2008
- [5] Baekhoej, S., Pedersen, J., Blaabjerg, F., Power Inverter Topologies for Photovoltaic Modules – A IEEE Review, 2002
- [6] Teodorescu, R., Lissere, M., Rodriguez, P., Grid converters for photovoltaic and wind power system, John Wiley and Sons, Ltd, New York, USA, 2011
- [7] \*\*\*, German Patent H5-Topology: DE 10 2004 030 912 B3, issued 19.01.2006
- [8] \*\*\*, German Patent HERIC-Topology: DE 102 21 592 A1, issued 04.12.2003
- [9] Kerekes, T., Teodorescu, R., Lissere, M., Evaluation of Three-Phase Transformerless Photovoltaic Inverter Topologies, *IEEE Transaction on Power Electronics*, 24 (2009), 9, pp. 2201-2211

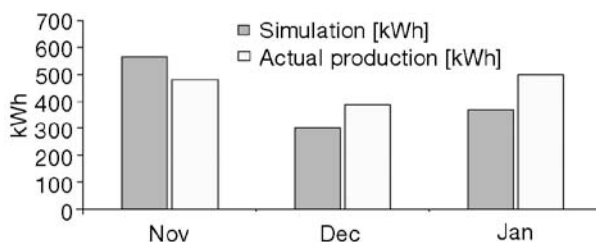


Figure 21. Comparison of simulation results and actual values

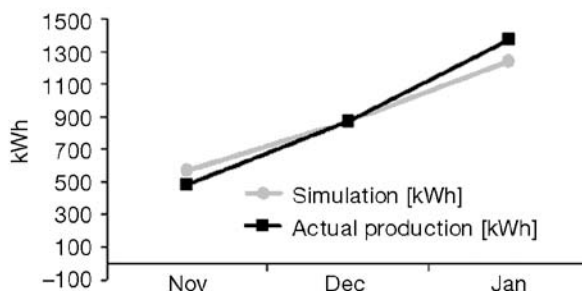


Figure 22. Cumulative production

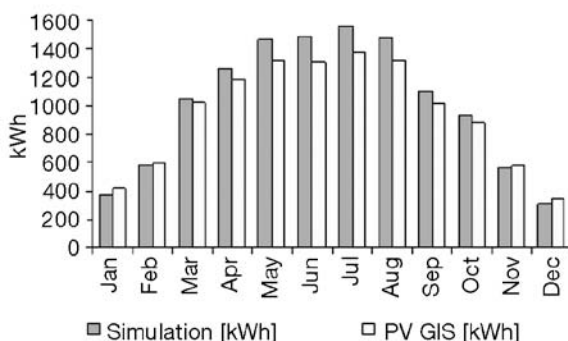


Figure 23. Comparison of simulation results and PVGIS