

Emulator of PV Panels for Laboratory Studies

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Abstract— The paper presents the realization of emulator of photovoltaic (PV) panels for laboratory studies in the Technical University of Sofia. First, the different possibilities for realization of such emulator are reviewed shortly. Then, is presented the emulator created in the Department of Electrical machines using power amplifier, controlled by PC. The connection between the power amplifier and the computer is verified by implementation of control algorithm in LabVIEW which imposes given reference for the output voltage of the amplifier. After this verification the PV emulator's control is implemented in the LabVIEW environment for simulation of the PV panel's behavior. For this purpose, is used an appropriate mathematical model of PV panel, based on single diode equivalent scheme. The model's equations are programmed in the LabVIEW environment and the possibility to obtain different I-V characteristics, corresponding of different meteorological conditions, is verified. Finally, the correct operation of the created emulator is verified and illustrated with different operation points that follow the I-V characteristic of the panel.

Keywords— PV emulator, power amplifier, LabVIEW environment

I. INTRODUCTION

The greater integration of generators using renewable energy in the electrical grids and the humans' life depends on the possibilities to control them [1]. Numerous researches are oriented to establish appropriate control strategy for photovoltaic (PV) and wind generators for grid connected or isolated operation mode, including maximum power point tracking (MPPT), limited or constant power point tracking (LPPT or CPPT), operation strategies for hybrid systems etc. [2]-[8]. The implementation of those strategies for the end customers needs experimental validation for various meteorological conditions which will guarantee robust operation. Unfortunately the renewable energies are intermittent [1] which impedes the fast and reliable validation and verification of the strategies. An appropriate solution of this obstacle is to replace the real generator, driven by a renewable energy, by something that is independent from the meteorological conditions and simulates the behavior of the generator. Thus, the wind generators can be replaced by combination of wind turbine emulator and electrical generator [9], [10], while the photovoltaic generator – by combination of PV panel and solar simulator or by PV emulator [11], [12]. A block diagram of renewable energy generator emulator is presented on Fig. 1. The emulator, of wind turbine or of PV panel, combines power converter and microprocessor or PC control. The control should implement the characteristics of the respective generator, I-V characteristics for the PV generator and power coefficient characteristics for the wind turbine using the power converter. Thus, it can imitate the real generator behavior when it's connected to the load or to grid.

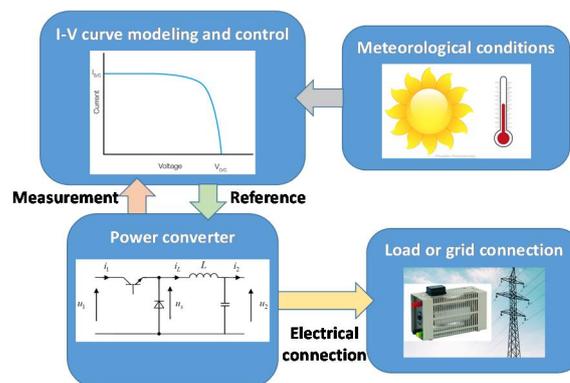


Fig. 1. PV emulator block diagram.

The aim of this paper is to present the realization of PV emulator using power amplifier and LabVIEW based PC control for laboratory studies in the Department of Electrical machines at Technical University of Sofia. First, short review and classification of the PV emulators is given and then the realization of the emulator is presented.

II. PV EMULATOR CLASSIFICATION

Since the domain is very important and interesting in the literature can be found many different realizations of PV emulators. Although the classification of this huge number of possibilities is a difficult task, in [13] is presented very good and exhaustive overview of the approaches to create PV emulator. Ayop and Tan propose a general classification according to the mains components of the emulator, presented on Fig. 1 – the I-V curve modeling, the power converter and the control strategy. Then they subdivide each group according to different other criteria. This classification of PV emulators is briefly presented below with some additional criteria and simplifications by the authors.

A. I-V curve modeling

For this part of the PV emulator two main criteria can be emphasized - the first one is the manner to obtain the I-V curve and the second one is the way to use the I-V curve model to generate the references for the power converter. According to the first criterion the emulators can be divided in following two groups:

- Emulators with model on the base of equivalent circuit;
- Emulators with interpolation on the base of already known points from the characteristic.

Regardless that it requires more calculation time, the electrical model of the I-V curve is the most used according to the review in [13]. Three possibilities for the equivalent circuit are available. They are summarized on the Fig. 2. The first

approach is to replace the PV model by current generator and diode (Fig. 2a). This approach is the simplest one but is not very exact because it neglects the serial resistance of the panel. The second possibility is obtained when this resistance is added to the first circuit (Fig. 2b). The precision here is improved without significant complications and this is the most used PV panel model. Fig. 2c shows the third possibility where the parallel parasitic resistance of the PV panel is taken in to account. The most complicated circuit has two diodes (Fig. 2d).

Each addition of further element requires supplementary information for the value of given parameter. Thus, the choice of the electrical model depends on the available information and the required precision.

The emulators with interpolation have simpler model without implicit equation but need information for different empirical or physical parameters.

The determination of the required parameters for both types of models (with equivalent circuit or with interpolation) gives another possibility to divide the models – the manner to obtain the required parameters. The possibilities are:

- Determination on the base of the manufacturer information at Standard Test Conditions (STC);
- Determination on the base of experimental data.

The first one is easier because the STC information is almost always available but the greater precision is achieved by the second one.

According to the way to generate the references for the power converter five methods can be used [13]:

- Direct calculation;
- Look-up table;
- Curve fitting;
- Artificial neural network;
- Curve segmentation.

The first three are more used while the last two are more exotic and less applied and respectively will not be considered here. The direct calculation requires high computing power and low memory capacity. It is applied only for simpler equivalent schemes. The look-up table method offers different possibilities for realization and is very used. The computing requirements are smaller but the memory should be greater than the first possibility. The curve fitting method is very simple and allows the use of low capacity controller. However, to achieve better precision it is necessary to increase the number of straight lines that replace the I-V curve.

B. Power converter

The power converter produces the necessary voltage and current according to the references. In general it is supplied by grid voltage after rectification. Thus, the power converters are principally step-down converters. This element of the PV emulator may be realized by one of the following conception [13]:

- Emulators with linear regulator;
- Emulators with switching-mode power converter;
- Emulators with programmable power supply.

The first conception has limited application because the losses in the linear regulator are relatively high. However, it has the advantage to respect the reference value correctly.

The second conception uses numerous different topologies of power converters with switching element (DC-DC converters). The most used are [12]:

- Buck converter;
- Buck-boost converter;
- Interleaved buck converter;
- Flyback converter;
- Forward converter etc.

The first three topologies are more used but don't provide galvanic insulation as the other two mentioned converters. The main advantage is the high efficiency because of the reduced losses and the simple control using the duty cycle. The main disadvantage is the presence of high frequency variations in the voltage and the current. Thus, the reference values may be not respected correctly. The most used DC-DC converter is the buck converter. Its topology is presented on Fig. 3.

The conception with programmable power supply is widely used due to its simplicity and because the power converter is already incorporated inside. However, it requires more powerful controller for I-V curve implementation.

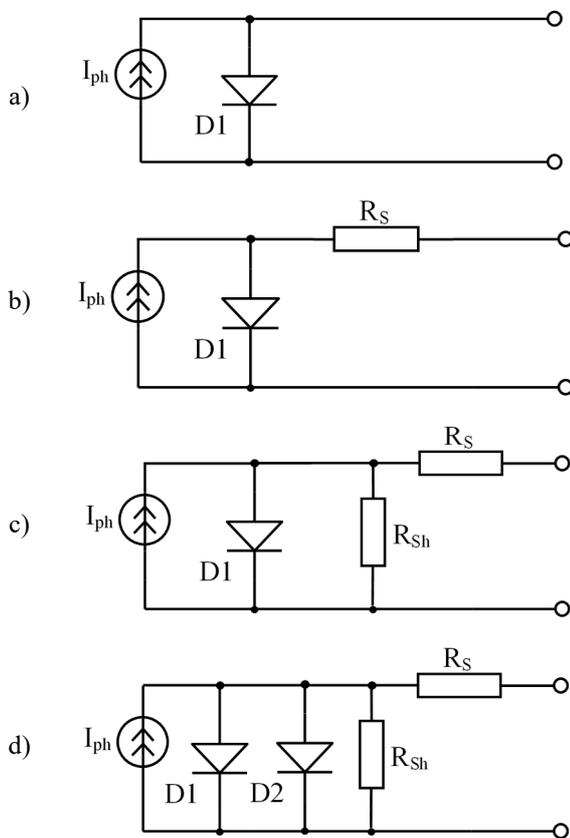


Fig. 2. Equivalent circuit of PV cell.

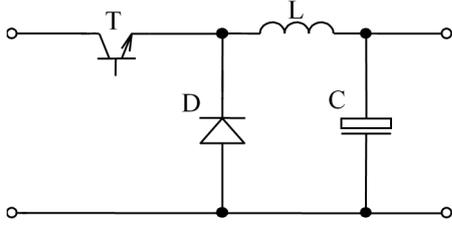


Fig. 3. Buck converter.

C. Control strategy

The control strategy is the way to generate and respect the reference value for the power converter. The authors of [13] propose very detailed overview of the possibilities, but the realization is not considered in this paper. Thus, they will be only listed. According to the controlled variable the approaches are:

- Voltage mode control;
- Current mode control.

According to the way to realize and respect the reference value the emulators are with:

- Direct referencing;
- Hybrid referencing;
- Perturb and observe referencing;
- Hill climbing referencing etc.

D. Controller type

The controller incorporates the I-V curve modeling, its implementation and the control strategy. Different possibilities are available. We can highlight the microprocessor systems and microcontrollers as:

- Arduino;
- dSpace;
- Texas Instrumens etc.

The control can be directly programmed in the microprocessor or realized with PC software that communicates with the microprocessor system. The most used software are LabView and Matlab. The choice of the software depends on the type of the microprocessor system.

III. PV EMULATOR REALIZATION

The PV emulator in the Technical University of Sofia is created using simplified PV model, implemented in LabView that controls a programmable power supply. The different parts of the emulator are detailed below.

A. PV model

The I-V curve is modeled by interpolation model. The main advantage of this model is that all required parameters can be determined from the manufacturer datasheet. The main modeling equation is [14]:

$$I_{PV} = I_{SC} \left[1 - C_2 \left(e^{\frac{V_{PV}}{C_1 V_{OC}}} - 1 \right) \right] \quad (1)$$

where I_{PV} and V_{PV} are respectively the current and the voltage of the PV panel, I_{SC} is the short-circuit current of the panel for the actual meteorological conditions, V_{OC} is the respective open circuit voltage, C_1 and C_2 are two constant determined by:

$$C_1 = N_S \frac{\frac{V_{MP}}{V_{OC}} - 1}{\ln \left(1 - \frac{I_{MP}}{I_{SC}} \right)} \quad (2)$$

$$C_2 = \left(1 - \frac{I_{MP}}{I_{SC}} \right) e^{-\frac{V_{MP}}{C_1 V_{OC}}}$$

where N_S is the number of serial connected cells, V_{MP} and I_{MP} are respectively the voltage and the current of the panel for the actual meteorological conditions at maximum power point.

The characteristic points (short and open circuit and maximum power) for the actual meteorological conditions takes into account the influence of the solar radiation and the ambient temperature on the values at STC. The solar radiation influence is determined by:

$$I_{SC(G_a)} = \left(\frac{G_a}{G_{STC}} \right) I_{SC(G_{STC})}$$

$$I_{MP(G_a)} = \left(\frac{G_a}{G_{STC}} \right) I_{MP(G_{STC})} \quad (3)$$

$$V_{OC(G_a)} = V_{OC(G_{STC})} + N_S V_T \ln \left(\frac{G_a}{G_{STC}} \right)$$

$$V_{MP(G_a)} = V_{MP(G_{STC})} + N_S V_T \ln \left(\frac{G_a}{G_{STC}} \right)$$

where G_a is the actual solar radiation, G_{STC} is the solar radiation at STC, index (G_a) means that the parameter value is for the actual solar radiation, while index (G_{STC}) is for the value at STC, V_T is the thermal voltage, calculated by:

$$V_T = \frac{kT}{q} \quad (4)$$

where $k=1.381 \cdot 10^{-23}$ J/K is the Boltzmann constant, T is the cell temperature in K and $q=1.602 \cdot 10^{-19}$ C is the electron charge.

The temperature influence is determined by:

$$I_{SC(T)} = I_{SC(T_{STC})} [1 + k_i (T - T_{STC})]$$

$$I_{MP(T)} = I_{MP(T_{STC})} [1 + k_i (T - T_{STC})]$$

$$V_{OC(T)} = I_{SC(T_{STC})} [1 + k_v (T - T_{STC})] \quad (5)$$

$$V_{MP(T)} = I_{MP(T_{STC})} [1 + k_v (T - T_{STC})]$$

where T_{STC} is its value at STC, k_i and k_v are the thermal coefficients respectively of the SC current and of the OC voltage, index (T) means that the parameter value is for the

real cell temperature, while index (T_{STC}) is for the parameter value at standard test conditions.

B. Power converter and control

The realized PV emulator uses programmable power supply to simulate the PV panel. The power supply is AMETEK XG1500-300-5. The supply's rated power is 1500W, its output voltage can vary from 0 to 300V, while its output current – from 0 to 5A. The programmable power supply is connected to the PC via USB connection. Thus, the I-V curve modeling and implementation can be realized with the LabVIEW software. To verify this possibility is created LabVIEW model on the base of examples, provided by the programmable power supply manufacturer. The model imposes random value for the supply's output voltage, measures the obtained voltage and calculate the difference between them. The LabVIEW implementation and the results are presented on Fig. 4. The left graphic shows the variation of the voltage reference, the middle graphic illustrates the obtained voltage variation and the right one – the difference between them. During this test with extreme variations the

error is limited to several mV and confirms the possibility to use LabVIEW for correct control of the power supply.

C. I-V curve model implementation

The interpolation model presented above is implemented in the LabVIEW environment (Fig. 5 left). The implementation is verified by visualization of the I-V curve for different values of the solar radiation. Only the result for $G_a=1000 \text{ W/m}^2$ is presented on Fig. 5 (right), but all results confirm the correct calculation of the I-V curve. The current is on the abscissa axis and the voltage on the ordinate axis.

After the calculation of the I-V curve that corresponds to the given meteorological conditions, a look-up table is used to determine the reference value for the output voltage of the power supply.

IV. EXPERIMENTAL VERIFICATION

The results from the experimental verification of the created PV emulator are summarized in Fig. 6. The figure shows the calculated I-V curve from the values for the

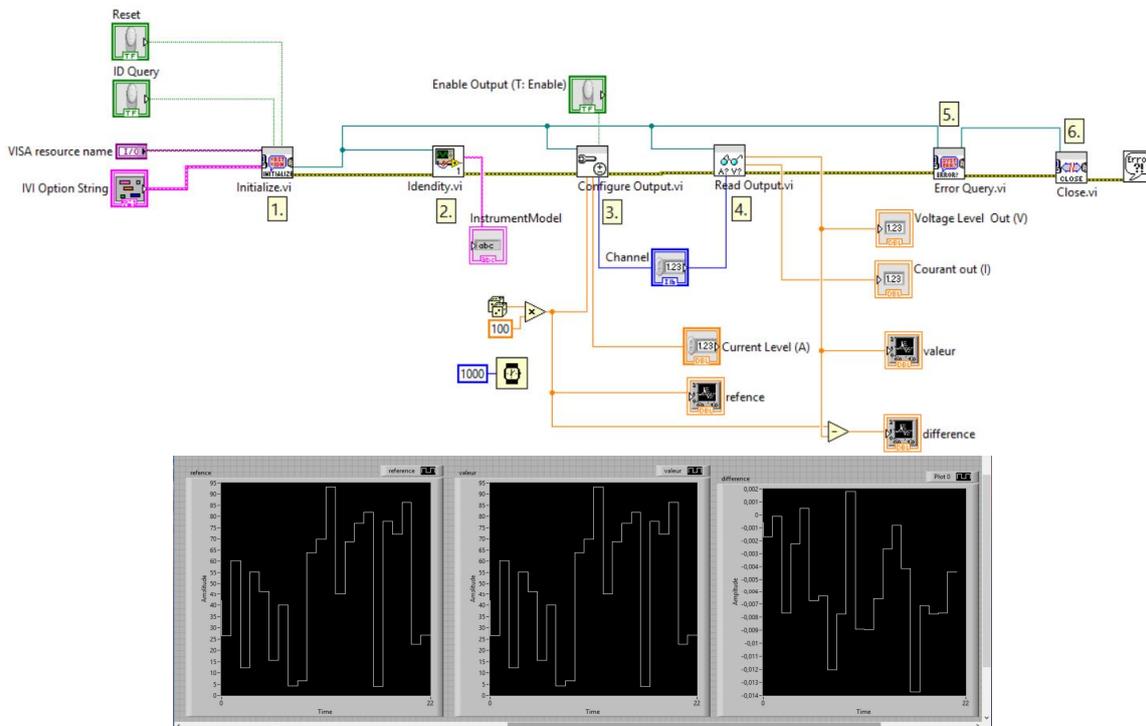


Fig. 4. LabVIEW control of the programmable power supply (up), reference voltage (down left), real voltage (down middle) and their difference (down right).

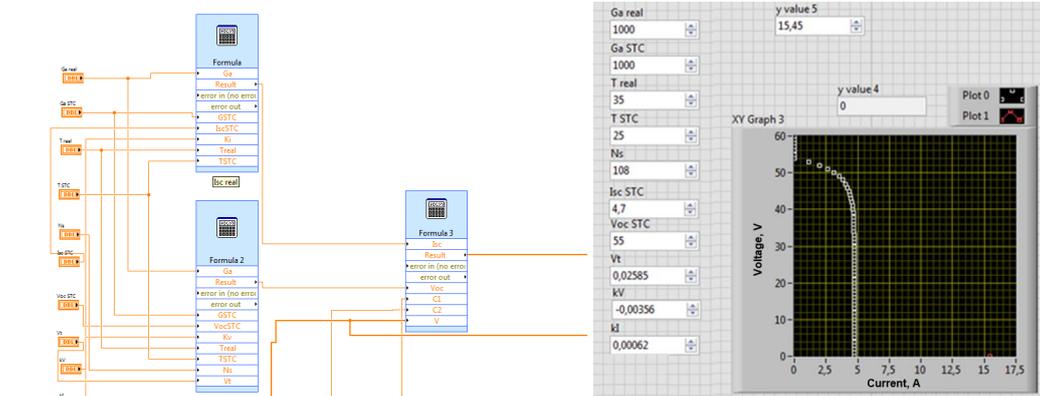


Fig. 5. LabVIEW implementation of the I-V curve model (left) and verification (right).

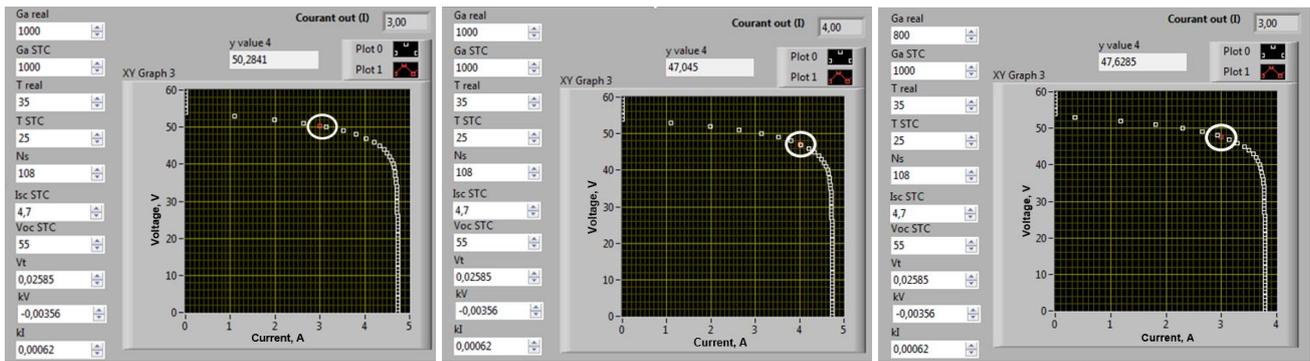


Fig. 6. PV emulator verification for different solar radiations and output currents: 1000W/m² and 3A (left), 1000W/m² and 4A (middle) and 800W/m² and 3A (right).

meteorological conditions. Combinations of two solar radiations (1000W/m² and 800W/m²) and two PV currents (3A and 4A). The left subfigure corresponds to the combination 1000W/m² and 3A, the middle subfigure is for the combination 1000W/m² and 4A and the right subfigure – 800W/m² and 3A. On each I-V curve with red is the calculated and respectively obtained operation point (highlighted with circle on the figures). The operation point is always on the I-V curve even though the variation of the curve in function of the meteorological conditions. This is indicator for the correct operation of the emulator. On this basis it's possible to enlarge the studies of different control strategies in the Renewable energy source laboratory (Electrical aspects) in Technical University of Sofia.

V. CONCLUSIONS

This paper presents the realization of PV emulator in the Renewable energy source laboratory (Electrical aspects) of Technical University of Sofia. The device will be used for different laboratory studies of PV panels in various configurations and control strategies. The I-V curve is modeled by interpolation model. The reduced precision of this approach is compensated by the absence of unknown or difficult for determination parameters. The model is implemented in the LabVIEW environment because it provides a lot of possibilities for control of the programmable power supply (AMETEK XG1500-300-5), which is chosen as a power converter in the emulator. The reference values are generated via look-up table and direct referencing. First, the supply control is tested by random variation of the output voltage reference. The error in the obtained actual value is limited in several mV and is very satisfying. The correct operation of the emulator is demonstrated by three experiments. They impose combination between two solar radiations and two current values for the simulated PV panel. The LabVIEW model calculates the respective I-V curve and the control algorithm generates the reference value for the voltage. The obtained operation point lies on the generated I-V curve. The correct operation will provide many possibilities for further studies in the laboratory.

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