SOLAR ARRAY SIMULATOR SYSTEM FOR TESTING THE BEHAVIOUR OF PV ELEMENTS*

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A solar module is the most important part of each photovoltaic (PV) system although, at the same time, it represents an energy source of low stability depending on many factors. All these factors are unstable for natural reasons but this is inevitable while producing the PV energy. A broad analysis of electric factors, influencing the performance of PV installations can only be carried out by means of a PV simulator, e.g. of the HPE 4350A type, independent of the solar activity, enabling the use and storage of data as well as their reproduction at any moment. The device allows to generate on demand any I=f(u) plot of characteristics on the basis of only four fundamental parameters i.e. I_{SC}, I_{MPP}, V_{MPP}, and V_{OC}. Any possible variant of the I=f(u) graphs, taking into account the influence of temperature, wind speed, module inclination, ageing etc., may be realized manually as well as, mainly, by means of the Solar Design Studio v 6.0 software. The paper presents exemplary test results covering battery charge controllers and showing the effect of a useful device on the assessment of the parameters of the components of an actual PV system.

Keywords: solar model, parmeters simulation

1. INTRODUCTION

Laboratory practice proves the self-evident truth that stable, long term and reproducible measurements on PV circuits and appliances powered by the modules

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irradiated by the sun are almost unrealisable. Only an artificial electric source with the sun-equivalent output characteristic may successfully perform the desired role, operating for a period of any length, irrespectively of the time of the day and the season of the year. Additionally, such a device should create the conditions simulating the influence of various irradiations, temperature, modules inclination, wind, light spectrum etc. Mostly preferable and useful would be the possibility to model any atypical shape of the I = f(u) function, even not existing in practice, but helpful in testing certain PV circuits and ideas [2].

All such features would be extremely useful in the entire PV technique area, especially when optimising the solutions of cooperating circuit and some separate elements of them. The above mentioned features and goals are fully realised by the Hewlett-Packard's E 4350 type solar array simulator. A view of a completely equipped PV testing stand with the E 4350A simulator is shown in Fig. 1.

Fig. 1. The view of the E4350A simulator with the cooperating computer and roof modules' control desk.
Rys. 1. Widok symulatora E4350A wraz z współpracującym komputerem i zbiorczym pulpitem modułów dachowych.

2. SELECTED SIMULATOR SPECIFICATION DATA

The E 4350 simulator offers a DC power output of the order of 450 W, being able to create I = f(u) PV plots of maximum 5 A and 120 V [5]. Such a range covers in practice most of the requirements of a medium power PV system and is especially suitable for testing the e.g. PV battery charge controllers, appropriate for such a popular power range and thus common on the market and in use. In the I = f(u) plot designing and programming processes useful are as usual the I_{SC}, I_{MPP}, V_{MPP} and V_{OC} parameters, which are basic and sufficient for the simulator to produce

the proper PV plots from the utility grid energy. Besides, a library of ready-made I = f(u) plots typical for many popular factory-made module types is available for the simulator. All of these modules may be compared under various irradiation and other conditions and this allows to make an optimum choice in any particular case. On demand, almost any shape of any PV I = f(u) plots may be generated by entering even 4000 pairs of coordinates producing jointly a curve, even of a form not observed in practice. All programming operations can be carried out manually as well as by means of a computer program called Solar Design Studio v 6.0 linked up to the simulator by the Agilent Technologies 82357B Type USB/GPIB interface [6]. The afore-mentioned program bases on five module equations [1]:

$$I_{sc}(E, T_c, AM_a, AOI) = (E/E_o) f_1(AM_a) f_2(AOI) \{I_{sco} + a_{Isc}(T_c-T_o)\} \tag{1}$$

$$E_e = I_{sc}(E, T_c = T_o, AM_a, AOI) / I_{sco} \tag{2}$$

$$I_{mp}(E_e,T_e) = C_0 + E_e\{C_1 + a_{Imp} (T_c-T_o)\} \tag{3}$$

$$V_{oc}(E_e,T_e) = V_{oco} + C_2 \ln(E_e) + b_{Voc} (T_c-T_o) \tag{4}$$

$$V_{mp}(E_e,T_e) = V_{mpo} + C_3\ln(E_e) + C_4\{\ln(E_e)\}^2 + b_{Vmp}(T_c-T_o) \tag{5}$$

where:

$E =$ plane-of-array (POA) solar irradiance using broadband (thermopile) pyra- nometer measurement corrected for angle-of-incidence sensitivity, W/m^2

$E_e =$ "effective" irradiance, dimensionless, or "suns",

$ln(E_e) =$ natural logarithm of E_e,

$E_o =$ reference "one sun" irradiance on array, 1000 W/m^2,

$AM_a =$ absolute air mass, dimensionless,

$AOI =$ solar angle-of-incidence on module, degrees,

$T_c =$ temperature of cells inside module, °C,

$T_o =$ reference temperature for cells in module, e.g. 50°C

$f_1(AM_a) =$ empirically determined "AM_a-Function" describing solar spectral influence on I_{sc},

$f_2(AOI) =$ empirically determined „AOI-Function" describing the influence of angle- - of-incidence on I_{sc},

$I_{sco} =$ $I_{sc} (E = 1000 \ W/m^2, AM_a = 1.5, T_c = T_o \ °C, AOI = 0°)$,

$I_{mpo} =$ $I_{mp}(E_e = 1, T_c = T_o°C)$,

$V_{oco} =$ $V_{oc}(E_e =1, T_c = T_o°C)$,

$V_{mpo} =$ $V_{mp}(E_e =1, T_c = T_o°C)$,

$I_{sc} =$ I_{sc} temperature coefficient, A/°C,

$I_{mp} =$ I_{mp} temperature coefficient, A/°C,

$V_{oc} =$ V_{oc} temperature coefficient, V/°C,

$V_{mp} =$ V_{mp} temperature coefficient, V/°C,

$C_0, C_1 =$ empirical coefficients relating I_{mp} to irradiance,

$C_2 =$ empirical coefficient relating V_{oc} to irradiance,
$C_3, C_4 =$ empirical coefficients relating V_{mp} to irradiance.

All the auxiliary data needed to perform visually the desired I = f(u) plot are entered into a special program of own design, called SOL-GPIB, by means of which they are inputted into the simulator memory. The program enables to load a file of the solar module characteristic, generated by another program and to transfer this characteristic to the E4350A simulator via the afore-mentioned interface. After creating the desired characteristic, the program performs the read-out of the current and voltage values every second, graphically exhibiting them in the form of two intersected lines against the background of I = f(u) and P = f(u) graphs drawn on the screen. Additionally, the program allows to remotely switch on and off the simulator output voltage. The data values, parameters and names become visualized on the computer display on the margins of the entire dialogue window (Fig. 2).
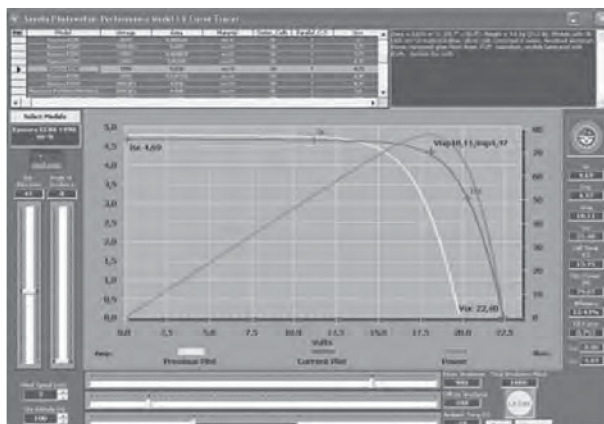
Fig. 2. Exemplary view of the simulator dialogue window with displayed curves and data for the chosen Kyocera KC80 module [7].
Rys. 2. Przykładowy widok okna dialogowego symulatora z eksponowanymi wykresami i danymi wybranego modułu typu Kyocera KC80 [7].

Apart from two basic I = f(u) graphs, a valuable P = f(u) function is displayed for one of them in this window [4]. According to the one-diode electric model of the PV solar cell, this function is described by the equation:

$$P = u \cdot I_S \left(\exp\frac{eV_{OC}}{mkT} - \exp\frac{eU_L}{mkT} \right) - i^2 R_S \quad \text{where:} \quad i = I_S \left(\exp\frac{eV_{OC}}{mkT} - \exp\frac{eU_L}{mkT} \right) \quad (6)$$

where: I_S – junction saturation current,
U_L – voltage on the load,

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u　　　 – cell voltage.

m　　　 – the ideality factor not including the influence of the cell series resistance,

V_{OC}　　 – open cell voltage,

k　　　 – Stefan-Boltzman's constant.

T　　　 – temperature in K.

3. EXPERIMENTAL

A basic circuit that allows to carry out fruitful investigations and measurements on PV elements, especially on battery charge controllers of MPPT- and conventional type – is presented in Fig. 3.
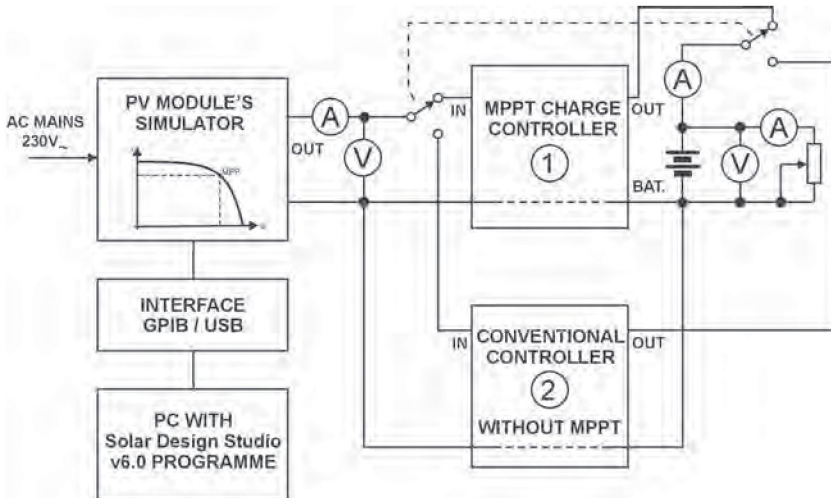
Fig. 3. Basic reference circuit for a comparative study of the efficiency of two main charge controller types.
**Rys. 3.** Podstawowy układ porównawczy do badań sprawności 2-ch zasadniczych typów regulatorów ładowania.

By means of it, precise comparative measurements are possible provided the same supply sources – i.e. the module simulator – as well as loads – i.e. the battery – are used. The presented system is especially suitable for comparing the efficiency of the DC/DC inverters integrated into the MPPT controllers before and after inserting the investigated variants as well as the efficiency of different types of battery charge controllers. The total efficiency parameter is crucial for the assessment of all controller types. More detailed information in [3].

The circuit shown in Fig. 3 enables also other important temperature measurements when comparing two controller types chosen at random, the one with and

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the other one without MPPT. Thus, interesting plots of controller output current vs. temperature may be obtained while maintaining constant irradiance and battery voltage parameters.

Six exemplary temperature/current characteristics for two controller types with irradiance and battery voltage as parameters are shown in Fig. 4, as plotted by means of the circuit shown in Fig. 3.

(a)

(b)

(c)

(d)

(e)

(f)
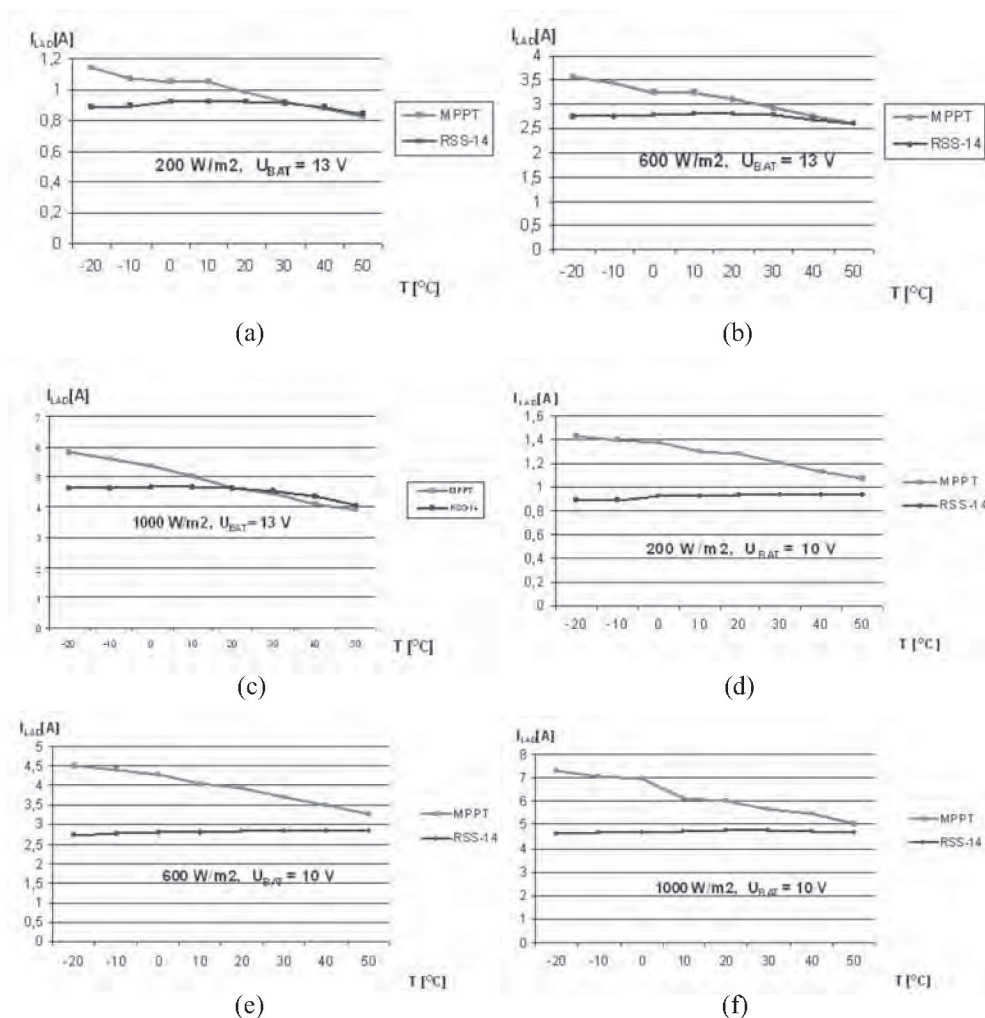
Fig. 4. Six exemplary I = f(T) curves (a - f) plotted for two different charge controller types (one MPPT, one conventional RSS-14 type) under simulated conditions according to Fig. 3. **Rys. 4.** Sześć przykładowych wykresów I = f(T) (a - f) sporządzonych w warunkach symulacji dla 2-ch typów regulatorów ładowania zgodnie z Rys. 3 (dla wersji MPPT i konwencjonalnej wersji typu RSS-14).

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In a standard laboratory practice, a sophisticated wide temperature range chamber with an inlet for solar irradiation would be indispensable for obtaining such diagrams and characteristic curves, while the measurement time effort itself appears to be completely incomparable. Moreover, no other circuit as that in Fig. 3 allows such an easy and fast selection of the optimum properties of the inductor and other elements while designing and testing the main MPPT circuit – i.e. the DC/DC inverter.

4. CONCLUSION

In comparison with all designing and testing PV methods – the use of a solar array simulator is no doubt the best practical way to produce on demand any type of any stable and reproducible shape of artificial solar irradiation characteristics. The possibility to influence almost all parameters of the generated $I = f(u)$ characteristics makes the simulator the most useful and irreplaceable tool of the entire PV technique, especially as it depends on neither the time of the day nor the season of the year. The simulator output power simply comes from the utility power grid and is separated and produced by a very complex computer-aided circuitry.

The properties of the simulator, especially of the HPE 4350A type, enable to test the behaviour of almost all PV system elements, allowing the choice of the best design solution and circuit variant. This especially applies to such crucial device as the battery charge controller whose components can easily be checked and assessed, like in no other way.

5. ACKNOWLEDGMENTS

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SYSTEM SYMULACJI MODUŁU SOLARNEGO DLA CELÓW BADANIA ELEMENTÓW FOTOWOLTAIKI

Moduł fotowoltaiczny jest najbardziej odpowiedzialną częścią każdej instalacji fotowoltaicznej (PV), prezentując jednak źródło energii o niskiej stabilności, zależnej od wielu czynników. Wszystkie one są niestabilne z naturalnych powodów, co jednak jest nieuniknione przy pozyskiwaniu energii PV. Rozległa analiza czynników wpływających na sprawność instalacji PV możliwa jest jedynie przy użyciu symulatora, np. typu HPE 4350A, niezależnego od aktywności słońca, umożliwiającego eksploatację, pamięć danych i ich odtwarzanie w dowolnej chwili, bazując na podstawowych parametrach I_{SC}, I_{MPP}, V_{MPP} i V_{OC}. Wszelkie możliwe warianty charakterystyk $I = f(u)$ uwzględniających wpływy temperatury, wiatru, nachyleń modułu, starzenia itp. mogą być modelowane zarówno ręcznie, jak i głównie z pomocą komputerowego programu Solar Design Studio v.6.0. Praca przedstawia przykładowe wyniki testów, obejmujących regulatory ładowania, wykazujących wpływ wartościowego przyrządu na ocenę parametrów elementów rzeczywistej instalacji PV.

Słowa kluczowe: solar model, parmeters simulation