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An integrated approach for improvement of the efficiency of the photovoltaic system by using cogeneration

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The present study explores the possibility of increasing the efficiency of a stand-alone photovoltaic system through cogeneration - simultaneous production of electricity and low-temperature water heating. Optimal operation means to achieve the best performance of the photovoltaic system, with certain limitations, and the optimal will be what provides the best condition of the system. The extreme value of a certain accepted quality assessment functional plays the role of an optimality criterion. It has been found that improving the performance of the photovoltaic system can be achieved by finding the optimum between the production of electricity, water heating and solar radiation, which ensures the highest efficiency of the system. An experimental installation has been developed and the results of the study of the photovoltaic system with cogeneration has been shown. The results of this study confirm the feasibility of the proposed solution for the production of electricity and heat energy for water heating.

Keywords: Solar energy, Photovoltaic system, Cogeneration, Optimal operation, Efficiency.

INTRODUCTION

A number of types of photovoltaic system (PVS) exist. It is known that the electric power produced by the photovoltaic system (PVS) depends on a number of factors such as the new solar radiation, climatic weather (clear or cloudy day), ambient temperature, angle of inclination, temperature of the modules and others. All of them have a significant impact on the effectiveness of PVS. Depending on their weight on the work of PVS, the factors can be grouped into:

1) Seasonal: For example, the annual season. They determine the seasonal cycle of change.

2) With Random modification: They are essential for the efficiency of photovoltaic modules. The most important of these is the type of day. If the day is clear, then the expected amount of electricity received from the photovoltaic module will be the largest. Random factors with relatively less but constant importance are the area and type of the photovoltaic module, the location of the photovoltaic installation and others.

3) Periodical: The time of day.

All of these are presumptive established effects can be classified as uncontrollable factors, as the power obtained from the photovoltaic module changes over time under their influence [18].

The efforts of many researchers are aimed at improving the performance of PVS. In this regard, new materials, technological and technical solutions are being developed to increase the efficiency of solar energy conversion. These efforts can be summarized in two large groups - the creation of new semiconductor materials, in which the conversion of solar energy directly into electricity is as efficient as possible through the combined production (cogeneration) of another type of energy [7, 8]. The purpose of all these solutions is to reduce the required area of photovoltaics by increasing the density of solar energy flux.

The main problem of direct conversion is the relatively low efficiency - between (10 -15) %. The rest of the solar energy that reaches the panels is converted into heat. In order to solve this problem, the multi-junction solar cells are being proposed, also, new types of solar cells are being created and more [11]. The rest of the solar energy that falls on the photovoltaic panels is converted into heat.

Another way to make better use of solar energy in PVS is through the combined production (cogeneration) of another type of energy [15]. A photovoltaic system with cogeneration allows for the simultaneous production of electricity and other energy. It is known that in the process of their work photovoltaics heat up. On the other hand, heating the photovoltaic panels further reduces their efficiency by 0.4 - 0.5% for every 1 °C at Standard Test Conditions (STC) - 1000 W/m² solar radiation level, 25 °C cell temperature and A.M. 1.5 air mass rate. Therefore, it is essential for photovoltaic modules to

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operate at conditions as close as possible to STC to obtain higher energy yields and better efficiency.

All this is a prerequisite for the combined production of energy from photovoltaic modules through the simultaneous production of electricity and heat.

A photovoltaic-thermal system (PVTS) consists of a PV panel and a thermal collector installed on the rear surface of the panel [4]. This makes it possible for the part of the solar radiation alighted on the surface of the photovoltaic panel to be converted into electrical power and heat [9, 19, 20].

In the literature, a number of authors have published their studies in the field of PVTS. In [6, 10, 19, 20] are suggested different profiles of thermal collectors. In [1] it was found that electrical, thermal and overall efficiencies reached 12.65%, 56.73%, and 85% respectively. A possible approach to cool it down through oiling tubes to the PV panel was presented in [17]. In [5] the energy and energy efficiencies of PVT air collector with monofacial solar cells and for the bifacial PVT were established.

The analysis of all this shows that the technical solutions are aimed at the joint development of electricity and heat (cogeneration) by solving the problem of cooling photovoltaic panels and at the same time improving the energy efficiency of PVS.

The purpose of this paper is to determine the optimal operating mode of a photovoltaic system using cogeneration for producing electricity and thermal energy.

The aim of this article is to study the efficiency of a stand-alone photovoltaic system through cogeneration - simultaneous production of electricity and low-temperature water heating.

MATHEMATICAL MODEL FOR THE OPTIMAL OPERATION

Optimal operation means to achieve the best performance of the photovoltaic system. Having in mind some limitations, the optimal would be what provides the best system state. Extreme value of an adopted function for quality assessment acts as a criterion for optimality [12, 13, 14]. The task is to find and maintain some extreme (maximum or minimum). In doing so, it comes down to determining the differential equation or the transfer function.

The solution of the considered problem can be reduced to minimizing the Hamilton function H [λ, x, y, t], written about a nonstationary system [2]:

$$\dot{x}(t) = A(t).x(t) + B(t).u(t). \tag{1}$$

If the minimum condition of the function H [λ, x, y, t] is applied with respect to the control u (t). This is equivalent to the condition for a minimum of $u(t) \in Q$ and at all points of continuity of the control of the function Λ [λ, x, y, t]:

$$min\,\Lambda[\lambda, x, u, t] = min\left\{\frac{dV[x(t), t]}{dt} + H[\lambda, x, u, t]\right\} = 0. \tag{2}$$

where: $V[x(t),t]$ is the Lyapunov function [16].

For each object, a certain relationship can be established between the relative yield q and the control effects u_j, $j=1 \ldots r$:

$$q = \sum_{j=1}^{j=r} \nu_j \left|u_j(t)\right|, (\nu_j > 0), \tag{3}$$

where: $\nu_j, j = 1 \ldots r$ are the coefficients of proportionality.

The total amount of energy produced in the interval [t_0, t_f] can be expressed by a functional of the form:

$$Q = \int_{t_0}^{t_f} \sum_{j=1}^{j=r} \nu_j .[u_j(t)] dt. , \tag{4}$$

while minimizing the functional (4), the process time

$$T = t_f - t_0 , \tag{5}$$

is not less than the minimum possible T^*. This time corresponds to the optimal speed process, i.e. $T \geq T^*$.

The control vector is assumed to be constrained as follows:

$$\left|u_j(t)\right| \leq 1; \; j = 1, \ldots, z. \tag{6}$$

Therefore, the managed system is of the form:

$$\dot{x}(t) = A.x(t) + B.u(t). \tag{7}$$

If the matrix A has eigenvalues with negative real parts, then the controlled object is stable. The free motion *x(t)* at $t \to \infty$ can be determined from the initial state $x(t_0) = x \neq 0$ to the origin of the coordinates $x(t_j) = x^j = 0$ for the control vector *u(t)* = 0:

$$\underset{t \to \infty}{x(t)} = e^{t.A}; x = 0 \tag{8}$$

Therefore, if the transition time is set $T_j = t_j - t$ (at negative eigenvalues of A) the trivial solution will be obtained $u^*(t)=0; T_j=\infty$. n doing so, the end time of the transition will be fixed:

$$t_j - t_0 = T_j \geq T^*, \tag{9}$$

where: T^* is the duration of an optimal speed process.

Record the Hamilton function for system (7):

$$H[x(t),p(t),u(t)] = \\ = \sum_{j=1}^{r} |u_j(t)| + \langle A.x(t),p(t)\rangle + \langle B.u(t),p(t)\rangle. \tag{10}$$

The condition for optimality is expressed by the relation:

$$\sum_{j=1}^{r} |u_j^*(t)| + \left\langle A.x^*(t),p^*(t)\right\rangle + \left\langle u^*(t),B^T p^*(t)\right\rangle \\ \leq \sum_{j=1}^{r} |u_j(t)| + \left\langle A.x(t),p^*(t)\right\rangle + \left\langle u(t),B^T p^*(t)\right\rangle, \tag{11}$$

where: $t \in [0,T_j]$ is performed for each admissible control u (t) bounded by (6).

Inequality (11) is equivalent to the following relation:

$$\sum_{j=1}^{r} |u_j(t)| + \left\langle u^*(t),B^T p^*(t)\right\rangle \\ \leq \sum_{j=1}^{r} |u_j(t)| + \left\langle u(t),B^T p^*(t)\right\rangle. \tag{12}$$

or

$$\sum_{j=1}^{r} |u_j(t)| + \sum_{j=1}^{r} u_j^*(t)\left\{\sum_{j=1}^{n} b_{ij}.p_j^*(t)\right\} \\ \leq \sum_{j=1}^{r} |u_j(t)| + \sum_{j=1}^{r} u_j(t)\left\{\sum_{j=1}^{n} b_{ij}.p_j^*(t)\right\}. \tag{13}$$

Switching functions are entered

$$\nu_j^*(t) = \sum_{j=1}^{n} b_{ij}.p_i^*(t); (j=1,...,r), \tag{14}$$

where $p_i^*(t); (i=1,...,n)$ are the solutions of (7).

Therefore, inequality (13) can be written in a more compact form:

$$\sum_{j=1}^{r} \left\{ |u_j^*(t)| + u_j^*(t).\nu_j^*(t) \right\} \\ \leq \sum_{j=1}^{r} \left\{ |u_j(t)| + u_j(t).\nu_j^*(t) \right\}. \tag{15}$$

The last inequality means that the function

$$H_m[u(t)] = \sum_{j=1}^{r} \left\{ u_j(t)| + u_j(t).\nu_j^*(t) \right\} \tag{16}$$

takes an absolute minimum at

$$u(t) = u^*(t); j=1,...,r);$$

$$\underset{u(r)\in\Omega}{H_m[u(t)]} = \\ = \sum_{j=1}^{r} \min_{|u_j(t)\leq 1|} \left\{ |u_j(t)| + u_j(t).\nu_j^*(t) \right\} \tag{17}$$

that is:

$$\min_{u(t)\in\Omega} H_m[u(t)] = \\ = \sum_{j=1}^{r} \min_{|u_j(t)\leq 1|} \left\{ u_j(t).\left[sign u_j(t) + \nu_j^*(t) \right] \right\} \\ = \begin{cases} \sum_{j=1}^{r} \left[1 - |\nu_j^*(t)| \right] & npu \quad |\nu_j^* > 1| \\ 0 & npu \quad |\nu_j^* < 1| \end{cases} \tag{18}$$

A sufficient condition for the normality of the problem is the performance for each *j=1,2,…,r* of:

$$det\left[G_j^T A^T \right] \neq 0, \quad (j=1,2,...,r), \tag{19}$$

where:

$$G_j = \left[b_j \vdots Ab_j \vdots ... \vdots A^{n-1} b_j \right]. \tag{20}$$

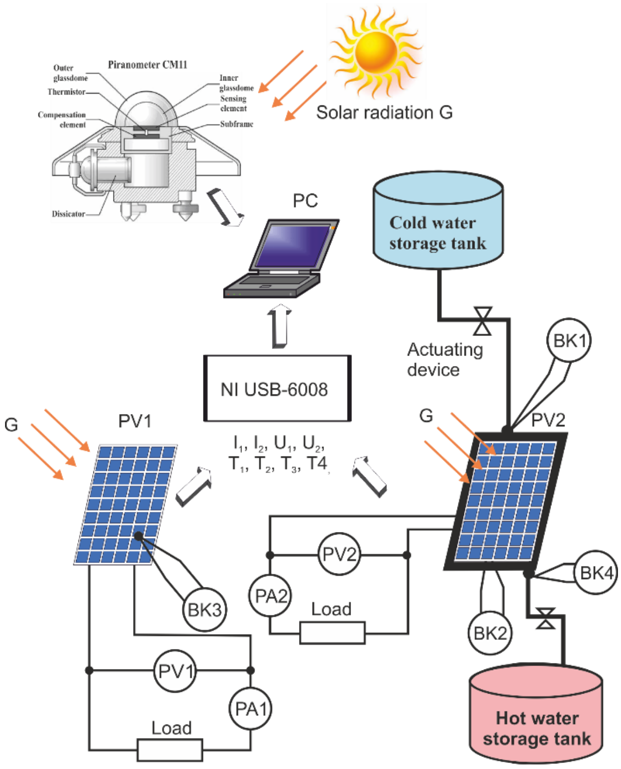
If the task is degenerated, it is necessary to optimize the operation of the system, i.e. for some equation i.e. for some j = 1,2,…, r, the equality should be in force:

$$det\left[G_j^T, A^T \right] = 0. \tag{21}$$

If the task is normal, this corresponds to the optimal operating mode.

RESULTS

Fig.1 shows the block diagram of the investigated autonomous PVT system. It consists of a photovoltaic panel PV1 without forced cooling, a cogeneration photovoltaic panel PV2 with water cooling, a charging controller; storage tank for cold and hot water; rechargeable battery, inverter and load, and the specialized measuring device NI USB-6008. It has 8 analog inputs, two analog outputs and 12 digital channels.



a

b

Fig.1. Layout (a) and the photo (b) of the investigated PV cogeneration system

Using the ammeters PA, the voltmeters PV and the temperature sensors BK, the magnitude of the current Ii, the voltage Ui, and the temperature Ti of the photovoltaic modules at constant load Load = const. are recorded, respectively.

The registered values are supplied in a suitable form and levels to the analogues in the input of the device NI USB-6008 in the range from -1 to + 10V. From it the data is transferred via USB cable in real time to a personal computer, for storage, processing and analysis.

The research of the solar radiation was performed with the help of a specialized measuring system of the company Kipp & Zonen B.V. It consists of a pyranometer CM11 and an integrating unit - Integrator. This instrument measures global solar radiation. The pyranometer has the spectral response of between 335 and 2200 nm. The integrated unit offers the possibility to directly in W,m^2 , or integrally in kJ, measure the intensity of direct and diffuse solar radiation. Through a standard communication serial interface (RS232) the processed signal from Integrator is fed to a personal computer.

With the help of specialized software, the obtained information about the intensity of solar radiation is visualized, stored and processed (Fig.2).

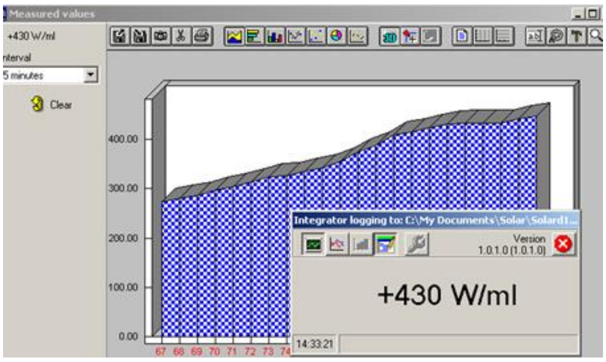


Fig.2. Working window of the software program Integrator [3]

The incident solar radiation on the surface of photovoltaic modules is the primary source of electricity production, but at the same time the modules are heated to a certain temperature. The two modules are mounted on a common stand and are oriented at the same angle to the Sun. On one of modules on the back is a tightly attached heat exchanger made of a spirally wound tube. Water is used as a heat carrier. The heat transfer from the photovoltaic module to the water is done through thermal conductivity and convection.

The heat flow (Q_t) can be determined by the expression:

$$Q_t = \Delta t.V.\rho.c.(T_2 - T_1), Wh \quad (22)$$

where:

Δt - interval of time in which the heat exchange was performed, h;

V – mass flow, l/h;

ρ – specific density, kg/l;

c - specific heat capacity of water (c = 4186,8 kJ/(kg. ºC);

T_1, T_2 are respectively the temperature of the water inlet and outlet, ºC.

The amount of heat that is released by the module and absorbed by the water can be determined by the calorimetric equation

$$Q = m.c(T_2 - T_1) \quad (23)$$

where:

m is the water mass, kg.

The heat transfer depends on the type and speed of the fluid, the area and the material of the heat exchanger. The speed of the fluid through the heat exchanger can be regulated by means of two taps mounted at the outlet of the cold tank and at the inlet of the hot tank by means of an actuating device.

The power P of the photovoltaic module increases with increasing solar radiation G and decreases with increasing temperature T.

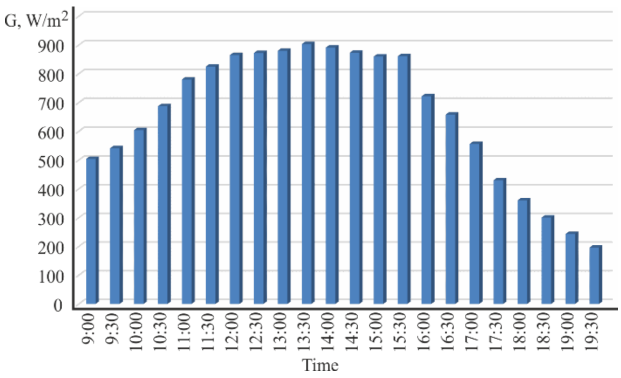


Fig.3. Dynamics of solar radiation G, W/m^2

The electrical efficiency η_{el} of the photovoltaic panel can be determined using the expression

$$\eta_{el} = \frac{P_{mp}}{G.A} \quad (24)$$

where:

P_{mp} – maximum power generated by the panel, W;

G – solar radiation, W/m^2;

A – area of the panel, m^2.

By differentiating (24) with respect to temperature, it is obtained

$$\frac{\eta_{el}}{dT} = \frac{1}{G.A}\left(I_{mp}\frac{U_{mp}}{dT} + U_{mp}\frac{I_{mp}}{dT}\right). \quad (25)$$

Therefore, the dependence on the electrical efficiency of the panel is valid:

$$\eta_{el} = \eta_{ref}\left(1 - \beta\left(T - T_{ref}\right)\right), \quad (26)$$

where:

η_{ref} – efficiency of cell at reference temperature;

β – cell's temperature coefficient, K^{-1};

T – module temperature, °C.

T_{ref} – reference temperature, °C.

On the Figs.3, 4 and 5 are presented obtained results.

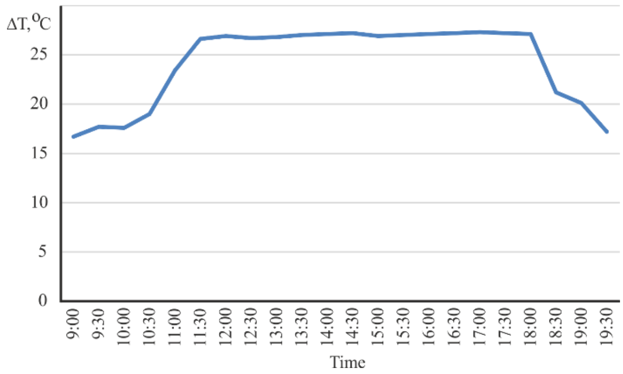


Fig.4. Temperature difference ΔT between PV1 and PV2, ºC

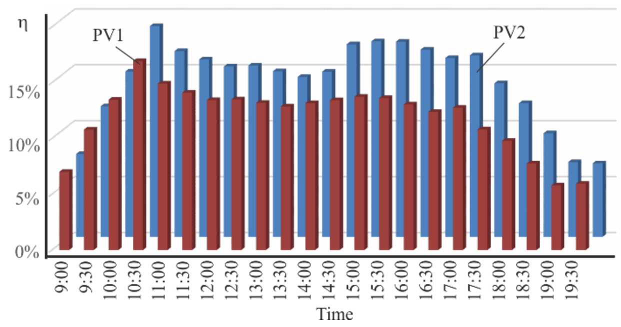


Fig.5. Efficiency dynamics η of PV_1 and PV_2

The analysis of the obtained dependences shows that the nature of the change in the intensity of the solar radiation during the sunny days is similar (see Fig.3). The minimal differences observed in size depend on the optical properties of the atmosphere. The change in function of astronomical time is parabolic, corresponding to the azimuth of the sun. The maximum intensity of solar radiation is observed in the middle of the day.

The positive effect of cogeneration is visualized in Figs.4 and 5. As a result of the heat exchange, the temperature of the photovoltaic panel with water cooling is almost constant, while the temperature of the other increases gradually with increasing solar radiation. The temperature of PV2 is from 20 to 24 ºC lower than PV1, with the largest difference observed during the hours with maximum levels of solar radiation. The resulting dependence has a trapezoidal shape and the horizontal section corresponds to the time range in which a PV system can be fully used for the production of electricity and heat. As a result of heat transfer, the water temperature rises by about 12.6 ºC.

Due to the cooling the generated current and voltage from PV2 are higher than those from PV1, respectively the electric power produced is higher. In addition, due to the relatively constant temperature of PV2 it is expected to have less heat load, and hence increase of service life.

The analysis of the dynamics of the efficiency η of PV1 and PV2 shows that the photovoltaic panel with cogeneration PV2 always has a higher efficiency compared to PV1. The efficiency of PV2 in electricity production is up to 30% higher than in the case of conventional air cooling, and the overall efficiency of the autonomous photovoltaic system increases from 12% to 14.1%. The thermal efficiency is 4,8% and the total efficiency of the investigated PV cogeneration system is up to 19%.

CONCLUSIONS

An approach is proposed to optimize the operation of a photovoltaic system by using cogeneration and increasing efficiency by achieving a balance between electricity and heat production.

An experimental system has been developed to study the operation of the PVT system. The obtained results prove the efficiency and feasibility of the proposed solution. The use of a heat exchanger reduces the heat load of the photovoltaic module, increases the generated electric power and low-temperature water heating.

The proposed approach is suitable for application in stand-alone photovoltaic systems, for combined production of electricity and heat and can be used in agricultural areas and remote sites where there are no centralized energy sources. It has been established that cogeneration makes it possible to increase the energy efficiency of photovoltaic systems.

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