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The influence of temperature of photovoltaic modules on performance of solar power plant

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Abstract: - Studies and research of photovoltaic power plants in real world conditions with a goal to find more effective control algorithms require significant investment in equipment and takes a lot of time. To accelerate the research, mathematical models are designed, which allow to simulate processes in photovoltaic power plant under conditions close to the real ones. To investigate the effects of temperature variations, the block of temperature is designed, which allows imitating the processes lasting for month or even several years. This block is used in a model of photovoltaic power plant, developed in earlier studies. The model described in this paper consists of four structural blocks: a block, imitating the solar energy flux; the block, for simulation of temperature variations; the block, imitating photovoltaic module and the control algorithm, in which the maximum power point tracking is performed using IncCond algorithm. The model of photovoltaic power plant is implemented in *Matlab/Simulink* environment. The model is used to investigate the effects of photovoltaic module temperature on performance of the power plant during a cloudy day. It is proved, that due to overheated photovoltaic modules the efficiency of power plant is decreased. It is proved, that it is possible to increase the efficiency of photovoltaic power plant from 11 % to 31 % applying forced cooling to all of the photovoltaic modules.

Keywords: *temperature of photovoltaic cell, maximum power point tracking, shadows.*

I. INTRODUCTION

Many researches are conducted with a goal to improve physical properties of photovoltaic (PV) cells. The efficiency of the most of PV cells is less than 20 %. Since the efficiency of PV cells is small, it is important, that they always operate at maximum power point (MPP). To maintain such operational conditions, special controllers, implementing different maximum power point tracking (MPPT) algorithms are used [1], [2]. The selected control algorithm influences how quickly MPP of the PV module will be found and how precisely it will be tracked.

MPP tracking in solar power plant is complicated because of unpredictably varying environmental conditions and different characteristics of different PV cells or modules. These differences can appear on some of the PV models of a single power plant if it affected be partial shadow, snow cover, hoarfrost, dust or tree leaves stuck on the surface of some PV modules. These effects are of random nature and it is impossible to predict their influence for different PV modules. Because of these effects it is not possible to predict the correct load of solar power plant at certain time intervals.

It is very important to keep the correct loading of PV modules, because only in this case the solar power plant will operate at MPP and will utilize the available solar power flux (SPF) with highest efficiency.

The position of MPP in current-voltage characteristics of PV module can vary because of temperature [3]. Earlier simulations were performed, assuming, that the temperature is 25°C and is constant. MPPT algorithms were investigated only depending on variations of SPF. However, in order to accurately assess and investigate the operation of solar power plant under conditions, close to real world, it is important assess the influence of variations of PV module temperature.

Studies and research of solar power plants in real world conditions require significant investment in equipment and takes a lot of time. This can be avoided by investigating the developed mathematical model of solar power plant and simulating real world conditions. This allows to compare the operation of solar power plant at certain time intervals, when only preferred parameters are changed.

In this work, the influence of temperature performance of separate PV modules and whole solar power plant is investigated. To achieve this, the Matlab/Simulink model, developed in previous works is used [4]. A block, imitating temperature variations at defined time interval is added.

II. INFLUENCE OF TEMPERATURE TO THE PERFORMANCE OF PHOTOVOLTAIC MODULE

From previous studies it is known that the power plant controller is particularly sensitive to rapid changes of SPF. However, it is not known how the controller responds when to main factors, influencing it`s operation are varying simultaneously – changing SPF and module temperature [5]. The operation of the solar power plant is studied in the following order: firstly the impact of environmental conditions on one PV model is studied, then on solar power plant, consisting of four PV modules.

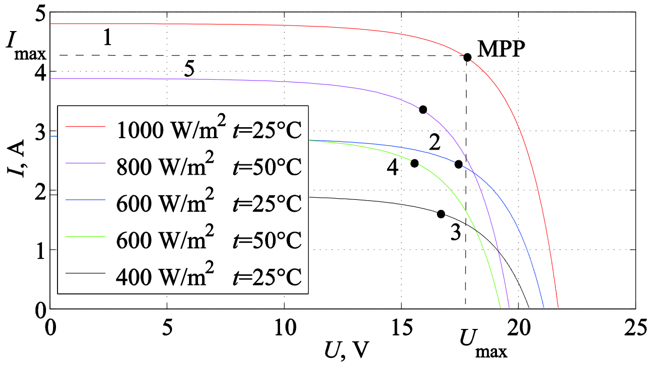

Figure 1 MPP at different SPF and temperatures [6]

Varying SPF, falling to the surface of PV module is simulated, when module temperature grows from 25°C to 50°C. Simulated current-voltage characteristics are presented in Fig. 1. The first series show the location of MPP, when PV module temperature is 25°C and it is illuminated by SPF equal to 1000 W/m^2. The second series show the location of MPP, when PV module is illuminated by SPF equal to 600 W/m^2 while the temperature is the same 25°C. The third series show MPP when SPF is only 400 W/m^2 and the temperature is still the same 25°C. These series characterize the location of MPP at the same temperature and different SPF. The fourth and fifth curves show the influence of temperature rise from 25°C to 50°C on the location of MPP.

Comparing first, second and third series reveals, that at constant temperature, the decrement of SPF causes significant decrement of PV modules output current. The decrement of SPF from 1000 W/m^2 to 600 W/m^2 causes the decrement of current by 1.9 A and voltage by 1.1 V. Thus power decreases by 32.7 W (series 1 and 2). When the temperature of the PV module is 50°C and SPF falls from 800 W/m^2 to 600 W/m^2 – the current decreases by 0.97 A and voltage –by 0.6 V (series 4 and 5). This causes the decrement of power by 14.2 W. When SPF is at constant level of 600 W/m^2 and temperature rises from 25°C to 50°C, the output current of PV module remains almost unchanged, but the voltage decreases by 2.3 V, so the power decreases by 9 W (series 2 and 4).

According to series 2 and 4 it is seen, that when the SPF is 600 W/m^2, the output power of PV module is higher at lower temperature. Analysis of the model proves that the increment of PV modules temperature decreases its efficiency, so less power is available at the output of the model at the same SPF. It can be stated that the characteristics of operation of PV module depend not only on SPF, but also on module temperature and it is necessary to keep it as low as possible.

III. STRUCTURAL DIAGRAM OF A MODEL

In Fig. 2 the structural diagram of solar power plant, for evaluation of temperature effects on performance is presented. In this model, the power plant can consist of the required number of PV modules. Each PV module consists of 28 PV cells. The overall power of the PV module at standard test conditions is 78 W. For this experiment four modules are being used so the total power of the solar power plant is 300 W. Similar signal ST, imitating SPF is sent to each PV module. It is generated by SPF block. The parameters of this block are selected in such a way, that it imitates SPF signal, close to the real one on a partially cloudy day.

To simulate the effects of temperature to the performance of the solar power plant, the temperature simulation block is used. In the model it is assumed, that all the modules are of the same type, and they are affected with the same solar radiation, so the same temperature signal is used for all the modules. Thus, these blocks simulate SPF and instantaneous temperature of the modules [4],[7].

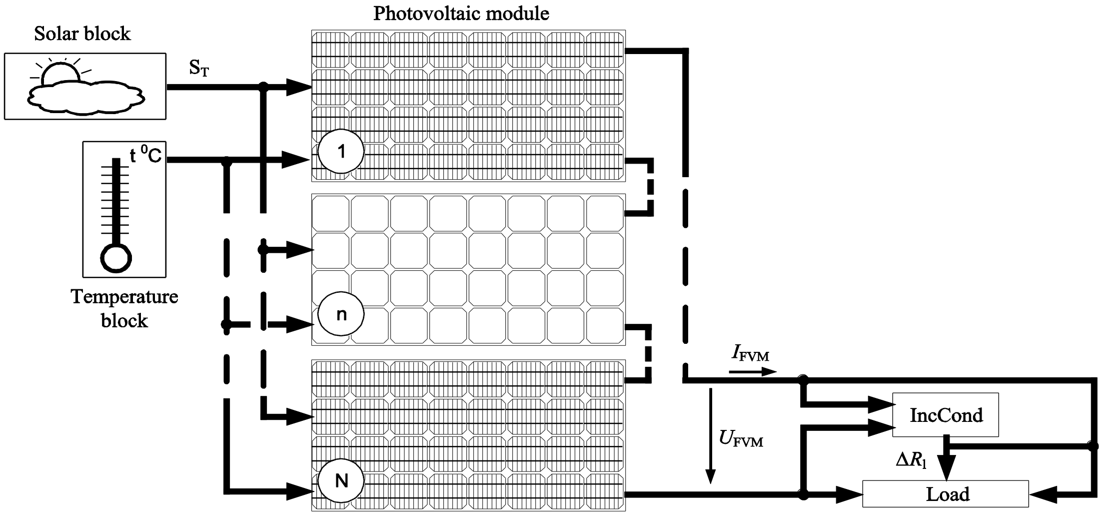

Figure 2 Structural diagram of a mathematical model

PV modules affected by SPF and temperature output voltage UFVM and the current IFVM, which flows through the load. In the analyzed solar power plant MPPT is performed according to IncCond algorithm [2]. According to the algorithm, PV modules output power derivative with respect to voltage dP/dU is calculated. The result describes the position of systems operation point in the power characteristic in relation with MPP. According to the results, the load resistance is increased or decreased by step ΔR_1.

IV. MATHEMATICAL MODEL OF SOLAR POWER PLANT

To investigate the influence of temperature variations on performance of solar power plant, according to described structural diagram (Fig. 2) the mathematical model is developed in Matlab/Simulink environment (Fig. 3). The core of the model is block, imitating SPF signal. This block has the following inputs: inclination angle, albedo, day of the year, longitude and time zone. These parameters can be adapted to simulate SPF falling to the inclined surface in any location on Earth at any time.

The model also includes the block to simulate cloud cover. This block attenuates the SPF signal and imitates additional diffused and reflected components of solar radiation. After applying Gaussian filter, the SPF signal, imitating real world conditions is formed [8].

The generated SPF signal imitates sunrise at 6:00 o'clock and sunset – 21:00 o'clock. Thus tem maximum power point tracking in solar power plant continues for 15 hours – the whole daylight time. The similar SPF signal falls to all four PV modules of the solar power plant.

The temperature of PV modules is defined in temperature simulation block, which sends generated signal to all PV modules. This block sets the temperature of PV modules depending on intensity of solar radiation and wind speed [9]. The goal of research is to determine the influence of temperature variation of PV modules on performance of solar power plant, when temperature changes rather fast (high wind speed) and slow (low wind speed).

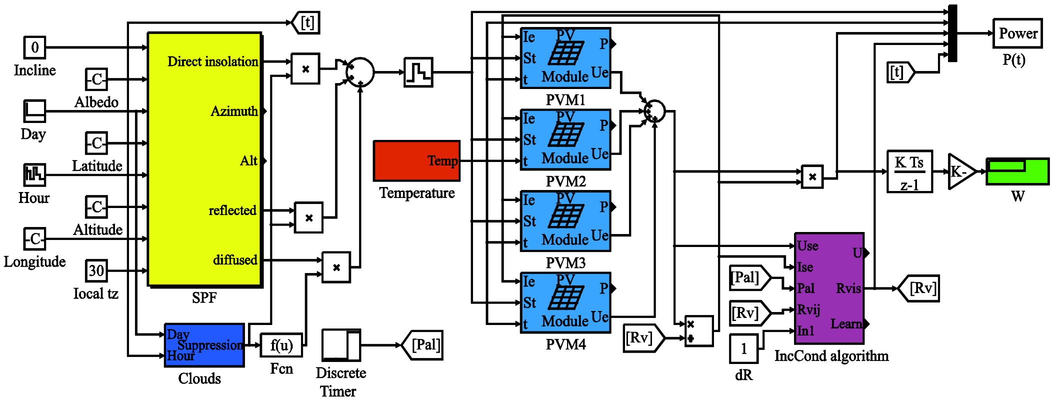

Figure 3 Matlab/Simulink model with temperature block

V. PLANT INCCOND ALGORITHM

In this work, IncCond algorithm is selected to perform maximum power point tracking [10]. This algorithm has simple control structure and is able to keep the system in MPP, when it is found. Simple mathematical implementation of algorithm allows achieving fast operation on the equipment with limited hardware resources such as embedded systems. The flowchart of IncCond algorithm is presented in Fig. 4.

The MPPT algorithm implemented in the model allows fast and precise finding of MPP and has the ability to keep the system in MPP, until the environmental conditions will change. Most of other algorithms are not able to precisely track MPP, and the system oscillates around it.

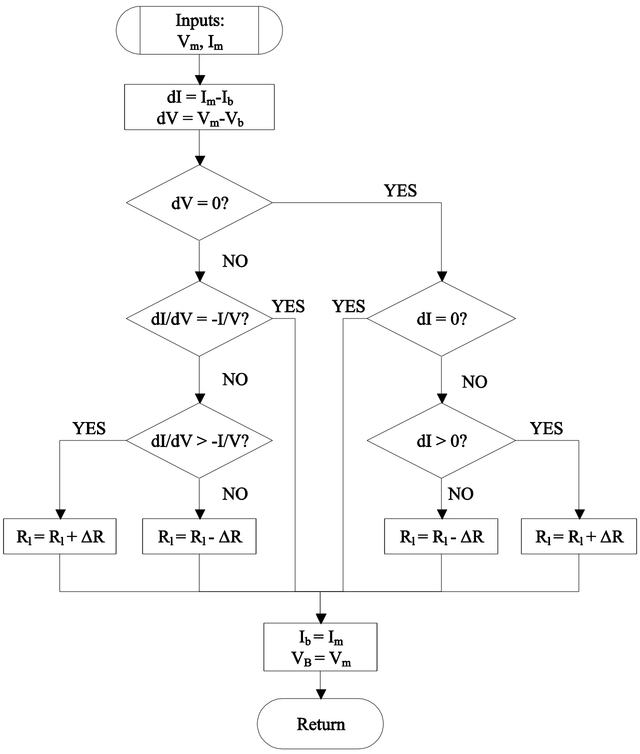

Figure 4 The flowchart of IncCond algorithm, implemented in the model of solar power plant

MPPT is performed by calculating the power derivative with respect to voltage.

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \tag{1}$$

Expression (1) allows to calculate the derivative in voltage-current characteristics and to determine the direction of change in load resistance. According to Fig 3 the load resistance changes can be described by these conditions:

$$\begin{cases} \dfrac{dI}{dV} > -\dfrac{I}{V}, & R_l = R_l + \Delta R, \\ \dfrac{dI}{dV} < -\dfrac{I}{V}, & R_l = R_l - \Delta R, \\ \dfrac{dI}{dV} = -\dfrac{I}{V}, & R_l = R_m, \end{cases} \tag{2}$$

where, ΔR – step of load resistance change, R_l – load resistance for PV modules, Rm characteristic load resistance, at which the PV module is operating with maximum power output.

The solar power plant operates at MPP when the third condition of expression (2) is satisfied.

VI. INFLUENCE OF TEMPERATURE ON PERFORMANCE OF SOLAR POWER PLANTS

A conclusion section must be included and should indicate clearly the advantages, limitations, and possible applications of the paper. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

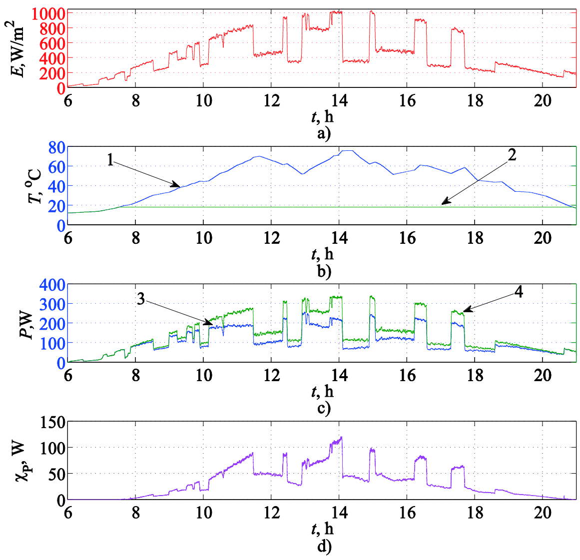

Figure 5 Solar power flux (a), temperature of PV modules during a slightly windy day without forced cooling (b-1), temperature of PV modules during a slightly windy day with forced cooling to 18°C (b-2), instantaneous power of solar power plant without forced cooling (c-3), instantaneous power of solar power plant with forced cooling to 18°C (c-4), instantaneous difference of output power (d).

In this work different environmental conditions were simulated in separate tests. First test assumed slow rate of change of temperature of PV modules, which sometimes rise to 75°C. This scenario is common for a clear day with small wind speed. Increasing the SPF causes the rise of PV modules temperature. The SPF chart, shown in fig. 6 a) imitates daylight time, when SPF varies from 0 to 1000 W/m^2. In fig 6 b) the first series show the variation of PV modules temperature during day. The second series show the temperature of PV modules when the forced cooling is engaged. Forced cooling is enabled when temperature reaches 18°C. In fig 6 c) series 3 show the instantaneous power at the output of solar power plant, when the forced cooling is not used and series 4 – when the temperature of PV modules is cooled to 18°C or lower. Fig 6 d) shows the instantaneous difference in power when the PV modules are not cooled and with forced cooling.

When the temperature of PV modules is dependent on environmental conditions, the solar power plant during a daylight time produces 1558 Wh of energy. During the same period of time and under the same environmental conditions, the solar power plant with forcibly cooled modules produces 2051 Wh of electrical energy.

The second test assumes the faster rate of change of PV modules temperature and it sometimes rises to 50°C. This pattern is typical for a day with a gusty wind. Strong wind causes faster cooling of PV modules, so their temperature cannot rise significantly. Fig. 7 a) shows SPF signal, which is similar to the previous test. In fig. 7 series 1 shows the dependence of PV modules temperature in dependence on SPF and series 2 shows the temperature of PV modules, when the forced cooling is used. In fig. 7 c) series 3 show instantaneous output power when PV modules are not cooled and series 4 – when forced cooling is used. Same as in previous test the comparison of output power between cooled and not cooled system is provided (Fig. 7 d)).

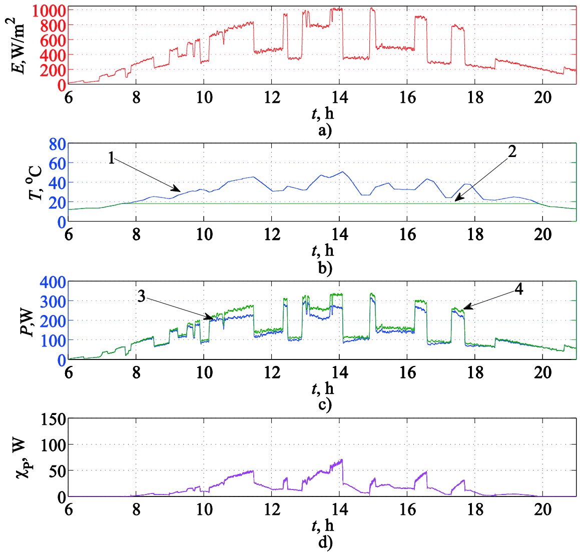

Figure 6 Solar power flux (a), temperature of PV modules during windy day without forced cooling (b-1), temperature of PV modules during windy day with forced cooling to 18°C (b-2), instantaneous power of solar power plant without forced cooling (c-3), instantaneous power of solar power plant with forced cooling to 18°C (c-4), instantaneous difference of output power (d).

When wind is gusty, the temperature of PV modules changes rapidly, and it does not rise significantly. During the 15 hours of daytime the power plant produces 1822 Wh of electrical energy. In case of forced cooling, when the temperature of PV modules is kept not higher than 18°C, the solar power plant produces 2029 Wh of electrical energy during the same period of time.

This study show that during the 15 hours of daylight, the amount of energy, produced in the solar power plant was by 264 Wh smaller when the temperature of PV modules changed slowly and reached 75°C. When the forced cooling of PV modules is used during a day with small wind speeds, the energy production of solar power plant increases by 492 Wh, and in case of a day with strong, gusty wing, the energy increment is 207 Wh.

VII. CONCLUSION

The efficiency of PV module decreases when its temperature increases. Studies have shown:

1. The efficiency of solar power plant can be significantly increased by applying the forced cooling of PV modules, especially, when solar power plant is installed in the location with small wind speeds.
2. Applying a forced cooling to PV modules and keeping their temperature not higher than 18°C, during a day with small wind speed, the electrical energy output of solar power plant increases by 31.5 %, compared to the case, when cooling is not used.
3. Applying a forced cooling to PV modules and keeping their temperature not higher than 18°C, during a day with strong, gusty wind, the electrical energy output of solar power plant increases by 11.3 %, compared to the case, when cooling is not used.

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