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Maximum Power Point Tracking in Solar Power Plants under Partially Shaded Condition

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***Abstract*—efficiency of solar cells is the biggest when the controller adjusts the load according to the temperature of the solar cell and solar energy flux. This task is accomplished by various maximum power point tracking (MPPT) algorithms. This paper presents the analysis of maximum power point tracking efficiency, when some modules of the solar power plant are partially shaded. Mathematical models of photovoltaic module and Incremental Conduction (IncCond) algorithm are implemented in Matlab/Simulink environment.**

The simulation is performed using saved solar power flux signal, imitating real-world environmental conditions. This signal allows to compare different working modes of MPPT tracker and to calculate the efficiency of the algorithm. It is proposed to use artificial neural network (ANN) to increase the efficiency of (IncCond) algorithm. Using ANN allows faster maximum power point tracking.

***Index Terms*—Maximum power point tracking, photovoltaic cells, shadows.**

I. INTRODUCTION

Modern inverters for solar power plants (SPP) are capable to perform maximum power point tracking. Total efficiency of solar power plant is highly dependent on MPPT performance, which determines the maximum amount of produced electrical energy. In solar power plants without maximum power point tracking energy losses can be up to 30 % higher than in the solar power plants with maximum power point tracking [1].

Different methods are used for maximum power point tracking. Currently, Incremental Conduction, Perturb and Observe and Ripple Correlation Control are the most frequently discussed and analysed MPPT algorithms in literature [2]–[4]. All these maximum power point tracking algorithms are rather slow to respond to the fast-changing weather conditions. Furthermore, most of them can not accurately detect the maximum power point.

Solar modules (SM) in solar power plants are connected in two ways – in parallel and in series. The topology of SPP is chosen according to desired system voltage and inverters input capabilities. When there are a lot of solar modules in the SPP, it is appropriate to use mixed topology (parallel branches of SM‘s connected in series). Current increases when modules are connected in parallel and the voltage increases when modules are connected in series [5], [6].

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In such way there are creating solar modules series and arrays in solar power plants. In addition, each solar module consists of photovoltaic cells (PV) connected in series.

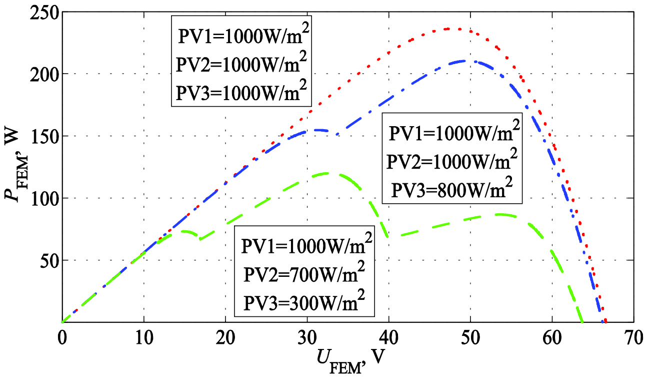

Fig. 1. Power – voltage characteristics of SPP, consisting of three serially connected SM‘s, operating under different partially shaded conditions.

There is a probability, that not all solar modules will receive the same amount of solar radiation in a SPP with series or array topology, due to availability of shadows. There is a risk of overheating and permanent damage when a single PV cell within a module is affected by the shadow. Bypass diodes are used in solar modules to protect the cells from overheating [7], [8].

Overheating is not the only problem caused by partial shadows. Due to shadows not all modules in the SPP are affected by direct solar radiation. In such conditions local maximum points can appear in power – voltage characteristics of SPP due to bypass diodes (Fig. 1). The figure presents the simulation results of SPP with different shading conditions. PV1, PV2, PV3 denotes solar power flux, falling on each of three solar modules of the plant. In Fig. 1 evenly illuminated (PV1 = PV2 = PV3 = 1000 W/m^2) SPP is presented and two cases when the shadow affects one (PV1 = PV2 = 1000 W/m^2 PV3 = 800 W/m^2) and two (PV1 = 1000 W/m^2 PV2 = 700 W/m^2 PV3 = 300 W/m^2) solar modules. It was considered during the test that the temperature of environment is 25^{0}C. Because of the local maximum power points, MPPT algorithms are not able to detect global maximum power point and can be stuck in one of the local maximum power points. Solar power plant is operating inefficiently if the control algorithm keeps the operation point of the system at a local maximum power point (MPP). This causes significant energy losses at the output of SPP.

To solve this problem it is necessary to improve algorithms for detection of global MPP by adopting artificial neural networks (ANN), which are getting popular in solar energy segment [9]–[12][11].

This paper presents the analysis of the influence of shadows to the performance of MPPT algorithms in solar power plants. Mathematical model of solar power plant with maximum power point tracking is presented and characteristics of solar modules with bypass diodes are analysed.

II. Mathematical Model

The mathematical model of shadow influence to operation of solar power plant (Fig. 2) is based on mathematical models of SPP developed in earlier studies [12], [13]. There is no possibility to estimate the influence of a bypass diode to the characteristics of SPP in Mathematical model, discussed in the previous [12] paper. Therefore, this mathematical model is complemented with a function of bypass diode. This allows more detailed analysis of operation of SPP.

Model of SPP consists of three solar modules connected in series to increase the voltage at the output of SPP. Peak power of each SM is 90 W at standard test conditions. Detailed module characteristics are presented in the Table I.

TABLE I. CHARACTERISTICS OF SOLAR MODULE.

Photovoltaic cells in a module	I_{max}, **A**	V_{max}, **V**	I_{sc}, **A**	V_{oc}, **V**	P, **W**
36	5	18	5,62	22,2	90

The model allows changing signal of the energy flux and temperature in each module separately. This allows simulating solar power plant operation when different modules receive different solar power flux. Such conditions are likely to appear in large solar power plants.

In presented SPP model separate block is designed to perform maximum power point tracking. IncCond algorithm is used for MPPT. In order to increase the efficiency of MPPT, additional signal for training of artificial neural network is provided at the output of MPPT block.

III. Influence of Bypass Diode to Characteristics of Solar Modules.

Most of solar modules have bypass diodes witch are already installed in factories. Usually one module has two bypass diodes.

The influence of bypass diode to SM characteristics is investigated in the model SPP consisting of two solar modules. The simulated current-voltage characteristics are presented in Fig. 3. Dotted curve represent the case, when both modules receive the same solar power flux PV1 = PV2 = 1000 W/m^2. Dashed curve shows the current-voltage characteristic, when modules receive different solar power flux (PV1 = 1000 W/m^2 and PV2 = 700 W/m^2) and bypass diode is not used. Dash-dot line shows the case, when modules receive different solar power flux and a bypass diode is used. It is considered that the temperature of solar modules is constant – 25^0 C. Analysis of simulation results, presented in Fig. 3 shows that bypass diode has a significant influence on the current-voltage characteristics when one of the SM is under shadow condition – bypass diode significantly reduces power losses in SPP caused by partial shadows.

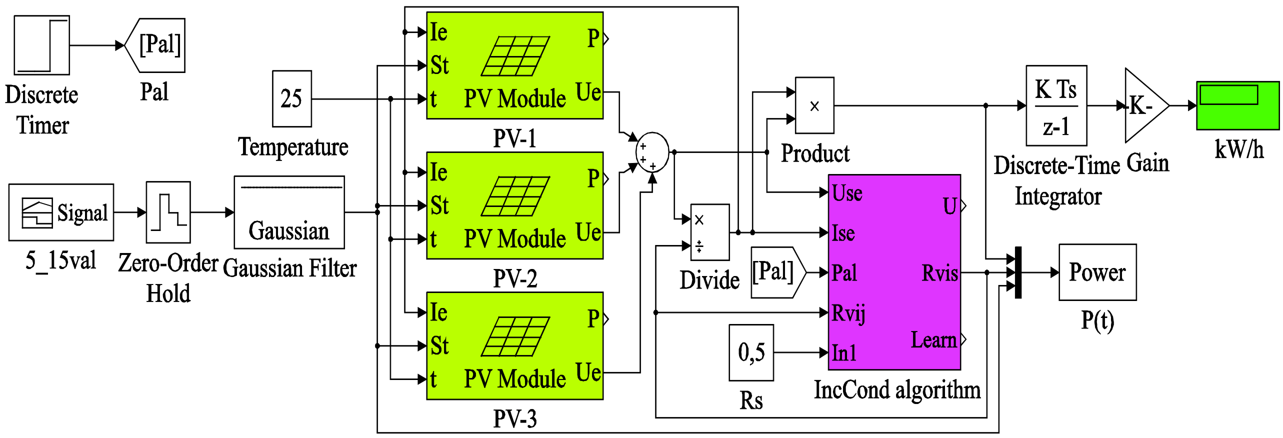

Fig. 2. Matlab/Simulink model of solar power plant.

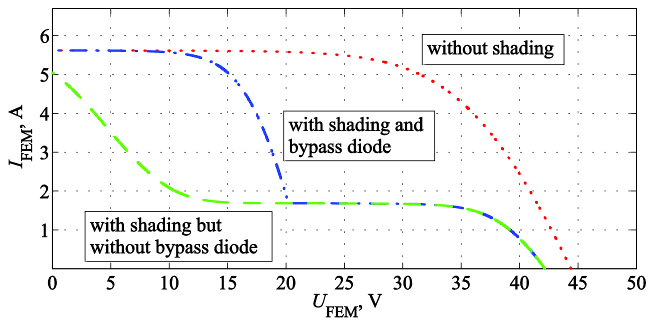

Fig. 3. Current-voltage characteristics of Solar power plant under different shading conditions with and without bypass diodes.

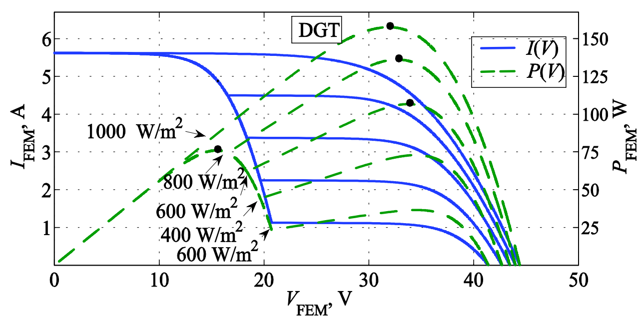

Fig. 4. Current-voltage and power characteristic of two solar modules.

To investigate the effects of partial shadows on SPP, simulations were performed when one of the modules receive constant solar power flux of 1000 W/m^2, while the solar flux, falling on the shaded modules surface is decreased in steps of 200 W/m^2. The results of simulation are presented in current-voltage and power characteristics in Fig 4. In this figure, continuous lines denote the current-voltage characteristics and shaded lines – power characteristics. The dot shows MPP on each of characteristics. Figure 4 shows that there are two maximum power points in power curves because of the bypass diode. When the solar power flux is more than 400 W/m^2 global maximum is located at the output voltage of the two solar modules. When the solar power flux is less than 400 W/m^2 global maximum is located at the output voltage of only one solar module. Analysis in Fig. 4 shows that power difference in the local and global MPP can reach 45 %.

The investigation of presented model showed, that the number of maximum power points in power characteristics depends on the number of the modules with bypass diodes. When wrong (local) maximum power point is detected by MPPT algorithm, an opportunity to utilize all available solar power flux is lost.

IV. IncCond Algorithm

In the presented mathematical model of SPP maximum power point tracking is performed according to IncCond algorithm [14]. This algorithm is selected because of its simplicity and the ability to detect and track maximum power point keeping the operation point of SPP at it. Also the simplicity of algorithms requires smaller computational resources what allows faster control process of solar power plant. The MPPT algorithm which is used in presented solar power plant model is shown in Fig. 5.

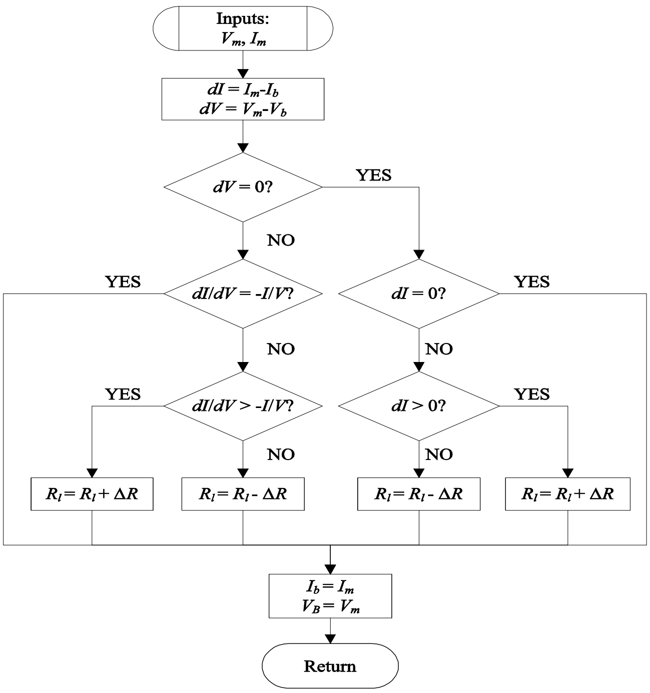

Fig. 5. Incremental Conductance algorithm.

MPPT algorithm used in the model allows the detection of maximum power point. After MPP is detected, operation point remains in it until environmental conditions are changed. During MPPT module output power derivative according to voltage is calculated

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

Derivative in expression (1) can be estimated in the current-voltage characteristic. This enables to detect in which side of maximum power point the system is operating:

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

where ΔR – step of load resistance change, R_l – load resistance, R_m – characteristic resistance, which corresponds to the current and voltage intersection.

In order to work in MPP expression (2) described the third clause must be matched. The detailed algorithm is shown in Fig. 5.

V. Influence of the Shadow in Solar Power Plants

To investigate the influence of shadows to operation of SPP the model is developed with three solar modules connected in series and having a peak power of 90 W. During the investigation different step load resistance values ΔR were tested to find optimal value, at which algorithm can reliably detect MPP and keep fast operation. Load resistance value is ΔR = 0,7 Ω. Characteristics of the solar power plant, operating during a daytime on August 14, is showed in Fig. 6. All three solar modules are operating at the same environmental conditions. The signal imitating 15 hours of rapidly changing solar power flux was simulated (Fig. 6(a)). In Fig. 6(b) curve 1 shows the variation of load resistance due to operation of MPPT algorithm and curve 2 shows the power at the output of solar power plant.

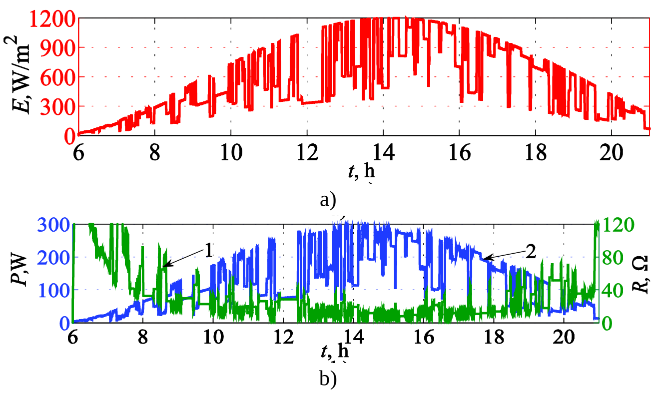

Fig. 6. Simulated signal of solar power flux (a) and load resistance, set by IncCond algorithm and the power at the output of solar power plant (b).

In Fig. 6 it is shown, the algorithm is not always able achieve optimal load resistance rapidly. However, when the environmental conditions are stable, the algorithm accurately detects MPP.

In further research the conditions, when different SM‘s of SPP are affected by different solar power flux were simulated. The solar power flux E_1, reaching the first module is shown in Fig. 7(a). Two remaining modules are affected by solar power flux signal $E_{2,3}$ (Fig. 7(b)). It was calculated, that under environmental conditions, presented in Fig. 7(a) and Fig. 7(b) the SPP with bypass diodes produced 1,92 kW/h and without bypass diodes – 1,73 kW/h of electrical energy during a day. This shows, that without bypass diodes control algorithm cannot track maximum power point correctly and the SPP operates at a mode, defined by the module receiving less solar radiation.

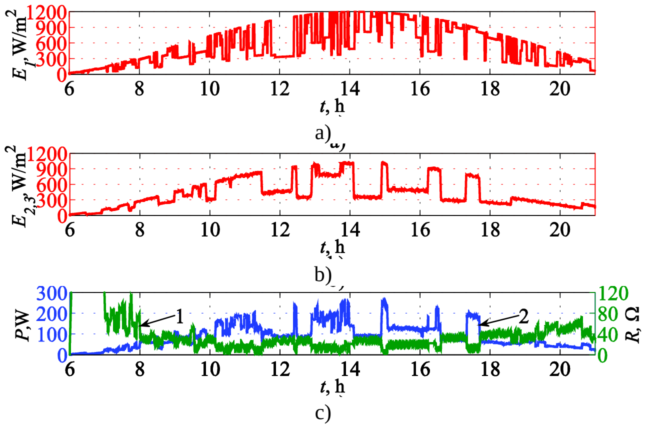

Fig. 7. Simulated signal of solar power flux (a), (b) and load resistance, set by IncCond algorithm and the power at the output of solar power plant (c).

When there is a small load resistance step, algorithm cannot find correct direction of maximum power point and get stuck (Fig. 8). This shows that when the algorithm detects a local maximum power point, it cannot get out of this point.

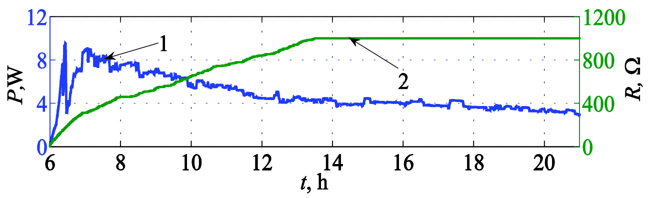

Fig. 8. Load resistance, set by IncCond algorithm and power of the solar power plant when the algorithm is stuck in the local maximum power point.

VI. Conclusions

The use of bypass diodes allows the output of electrical energy from SPP, affected by partial shadows, to be increased up to two times.

Local and global maximum power points appear in power – voltage characteristics under partially shaded conditions. The amount of these points is equal to a number of bypass diodes used in the SPP.

If the maximum power point algorithm sets and keeps the operation point at a local maximum, SPP cannot reach highest possible output power and part of solar energy remains unutilized. The difference of the output power of SPP operating in a local and global maximum point can reach 45 %.

Artificial neural networks can be used to avoid the continuous operation of SPP at local maximum power point.

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