

# Method for Prediction of the Power Output from Photovoltaic Power Plant under Actual Operating Conditions

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**Abstract.** Solar photovoltaic technology is one of the most rapidly growing renewable sources of electricity that has practical application in various fields of human activity due to its high availability, huge potential and environmental compatibility. The original simulation model of the photovoltaic power plant has been developed to simulate and investigate the plant operating modes under actual operating conditions. The proposed model considers the impact of the external climatic factors on the solar panel energy characteristics that improves accuracy in the power output prediction. The data obtained through the photovoltaic power plant operation simulation enable a well-reasoned choice of the required capacity for storage devices and determination of the rational algorithms to control the energy complex.

## 1. Introduction

The most serious technical problem of the photovoltaic (PV) power plant (PVP) operation is a strong dependence of power generation on the plant's geographical location and climate conditions. Therefore, a reliable prediction of the electrical power generation is crucial for the PVP design to enable the appropriate choice of the plant equipment that ensures the energy and economic efficiency of the PVP.

The data on the average daily values of solar radiation intensity at the installation site is primarily used to predict the plant power output:

$$W = L\eta_1\eta_2SN, \quad (1)$$

where  $W$  is the expected power output per day [kWh/d];  $L$  is the average daily value of solar radiation intensity per unit area for every month of the year [kWh/m<sup>2</sup>/d];  $\eta_1$  is the PV module efficiency;  $\eta_2$  is the overall efficiency of power conversion;  $S$  is the PV module area [m<sup>2</sup>];  $N$  is the number of PV modules in a solar panel.

The solar radiation intensity value in equation (1) can be determined either by calculating according to the known methods [1–3] or by using the meteorological databases [4–6]. The obvious



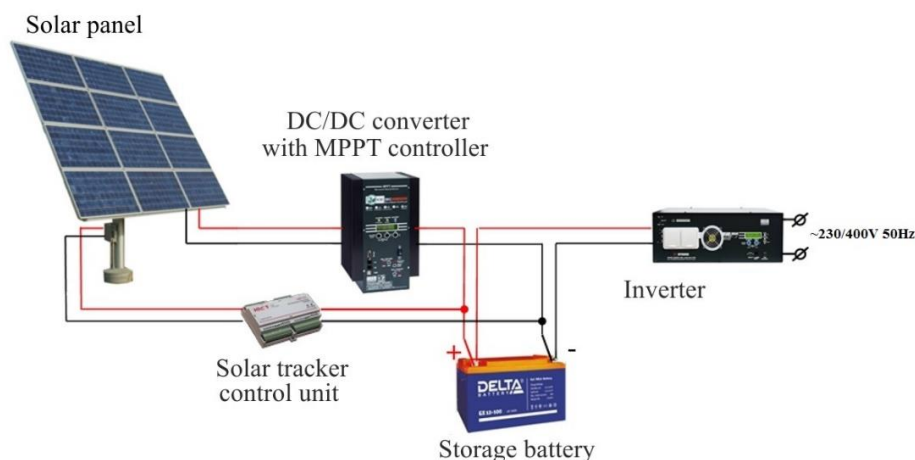
advantage of this approach is its maximum simplicity, but it does not take into account the actual operating conditions of the PV module operation.

In addition to the solar radiation intensity, the PV converter energy characteristics are affected by the PV module surface temperature, which in turn depends on the ambient temperature, electric load and wind speed. In the regions of Russia that have continental climates, the ambient temperature can vary over a wide range according to seasons of the year or within 24 hours that can lead to significant errors in the power output prediction.

The research aims to develop an improved method to predict the plant power output under actual operating conditions.

## 2. The object of the Study and the Method Requirements

The object of the study is a stand-alone PVP, its typical scheme is shown in Figure 1.



**Figure 1.** Scheme of the PV power plant.

The main elements of the PVP are the solar panel that consists of PV modules, DC converter controlled by the maximum power point tracking (MPPT) controller, the energy storage device, and the voltage output inverter. The PVP is often provided with the sun tracking system to improve its energy efficiency. In this case, the PVP also includes the solar tracker control unit and the tracking system operation unit based on the engines with gearboxes.

The main power equipment consistency requires careful coordination of the energy production and consumption modes. Thus, it is crucial to predict the hourly solar radiation arriving on the surface that is arbitrarily oriented to the sun and to determine the PV module energy characteristics with due regard to the external climatic factors. Non-linearity of the main PVP element characteristics and stochastic nature of the external meteorological factors significantly complicate the stated problem solution. This results in the necessity to use the mathematical modeling techniques.

The consistency of the individual components within a single system is essential to develop the PVP model, and therefore a single universal simulation tool is required. The mathematical package MatLab was used to run a simulation. The models of all the PV system components were implemented in Simulink as separate subsystems that enabled their use for simulation and study of the PVP modes of arbitrary configuration.

## 3. Mathematical Models of the PVP Individual Components

### 3.1 Model of Solar Radiation Arrival

The primary solar energy value available for conversion depends on the total solar radiation intensity at the installation site, geographical location of the plant, the solar panel spatial orientation, and the external meteorological factors: cloudiness level and surface reflection coefficient.

Most of the meteorological factors have a stochastic nature, and their time fluctuations vary from fractions of a second up to at least tens of thousands of years that eliminates the possibility of their reliable determination by the theoretical calculation methods. Therefore, the probabilistic (statistical) methods of calculating the radiation characteristics are currently used to design PVPs. The climatic manuals or electronic databases that provide the results of long-term weather observations are used as the initial data.

The total intensity of solar radiation hitting the surface, which is inclined and arbitrarily oriented relative to the tilt  $\beta$  and azimuth  $\gamma$  angles, is calculated according to the method proposed by Liu-Jordan [2], and the impact of cloudiness is determined by the Berlyand formula [7].

The initial simulation data are the PVP location latitude, azimuth and tilt angles of the solar panel orientation, number of the simulated day of the year, cloudiness level, surface albedo, and solar tracker type.

The model enables determination of the time values of solar insolation for any day of the year in any geographical location of the PVP. The theoretical method is used to calculate the insolation value for ideal conditions (clear sky). The insolation under cloudy conditions is calculated using statistical data of the meteorological databases and with due regard to the scattered radiation reflected from the earth's surface [4–6].

The model is developed as a subsystem that consists of eight separate functional units: data input unit, units for calculation of the sun height and azimuth, solar time of sunrise (sunset), solar radiation hitting the inclined area, the incidence angle of direct radiation, and units for the cloudiness level estimation and the output data preparation.

The long-term statistical data of solar radiation intensity [ $\text{MJ}/\text{m}^2$ ] on a horizontal surface in some regions of Russia located between latitudes  $40^\circ\text{N}$  and  $60^\circ\text{N}$  were used to verify the model. The performed numerical experiments showed that the solar radiation arrival model provides the adequate results of calculation of the solar energy resources: the root mean square error for individual months does not exceed 14% and is no more than 8% for the whole year.

### 3.2. Solar Panel Model

The majority of the solar panel models are based on mathematical equations that describe the processes in the equivalent circuit of a solar cell [8, 9]. In this case, the number of unknown variables in the resulting system of equations is greater than the number of equations. Therefore, the numerical methods with a small iteration step size are essential to solve the resulting system. This type of the solar panel models is primarily used for the analysis of dynamic processes in the PVP, but the models are inefficient to calculate the solar panel energy characteristics over long periods of time.

The method proposed by Jones and Underwood [10] was used to develop a simplified model of the solar panel. According to the method, the maximum output power of the solar panel is determined by:

$$P_{\text{out}} = C_{FF} N_m \eta_{\text{conv}} \frac{G \ln(10^6 G)}{T}, \quad (2)$$

where  $N_m$  is the number of PV modules in the solar panel;  $C_{FF}$  is a constant coefficient of the solar panel;  $\eta_{\text{conv}}$  is efficiency of the converter with the maximum power controller;  $G$  is the current level of global insolation,  $\text{W}/\text{m}^2$ ;  $T$  is the PV module current temperature.

The present study uses a more accurate equation to determine the coefficient  $C_{FF}$  in contrast to the original method [10]:

$$C_{FF} = \frac{FF T_{\text{ref}} [I_{SC} + k_I (T - T_{\text{ref}})] [V_{OC} + k_V (T - T_{\text{ref}})]}{G_{\text{ref}} \ln(10^6 G_{\text{ref}})}, \quad (3)$$

where  $FF$  is the fill factor of the PV module;  $T_{\text{ref}}$ ,  $G_{\text{ref}}$  are respectively the temperature and global insolation values of the PV module under reference conditions.

The fill factor of the PV module is determined according to its technical specifications:

$$FF = \frac{I_{MPP} V_{MPP}}{I_{SC} V_{OC}}, \quad (4)$$

where  $I_{MPP}$ ,  $V_{MPP}$  are certified values of the PV module current and voltage at the maximum power point under reference conditions;  $I_{SC}$ ,  $V_{OC}$  are certified values of the PV module short-circuit current and open-circuit voltage under standard conditions.

The simplified model of the solar panel was implemented as a subsystem and verified on a number of PV modules. The model showed a good agreement of the simulation results with the manufacturer's data. The initial data for calculation of the PV module characteristics are the current values of solar radiation, the semiconductor surface operating temperature, and the PV module parameters listed in its technical specifications.

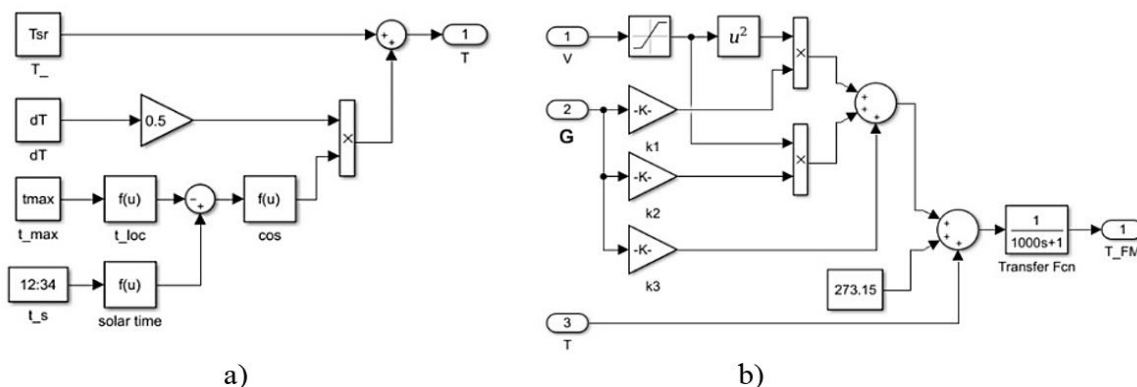
### 3.3. Model for Calculating the PV Module Surface Temperature under Operating Conditions

The solar panels located in the high northern latitudes of Russia are affected by the external meteorological factors, and therefore these factors must be taken into account. It is fairly simple to determine the average monthly ambient temperature and wind speed, which are independent from the designed installation parameters. The statistical data of meteorological observations that can be obtained from meteorological site archives are the initial data for determination of the air temperature and wind speed [11]. In contrast to the wind speed, changes in the diurnal temperature range in the northern latitudes can be determined by:

$$T(t) = \bar{T} + \frac{\Delta T}{2} \cdot \cos \left[ \frac{2\pi}{t_v} \cdot (t_{loc} - t_{max}) \right], \quad (5)$$

where  $\bar{T}$  is the average daily air temperature, [°C];  $\Delta T$  is the diurnal air temperature variation, [°C];  $t_v$  is the air temperature variation period, [h];  $t_{max}$  is local time of the temperature maximum, [h];  $t_{loc}$  is local solar time, [h].

The proposed method to develop the diurnal temperature range model can be easily implemented for any day of the year and any region using the statistical data of meteorological observations from the nearby weather station. The model is implemented as a subsystem and enables us to obtain time dependence of the temperature variation for the given day of the year using only 3 parameters (Figure 2,a).



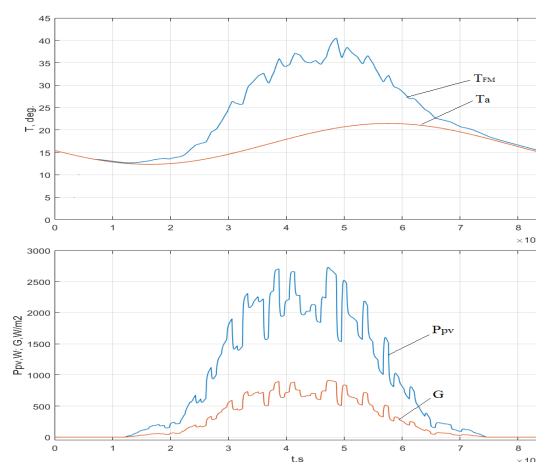
**Figure 2.** Model of the diurnal temperature range and model for the PV module temperature calculation implemented in MatLab/Simulink.

However, in addition to the ambient temperature impact, the PV module temperature is directly affected by the radiation energy arriving at the module surface along with the sunlight and the internal

heat sources that occur due to electrical losses in the solar cells and contact resistances. The PV module operating temperature is the result of a convective/radiant heat exchange between the module surface and the environment. Thus, the module current temperature cannot be determined by rigorous theoretical methods due to the impact of numerous factors: coefficients of the heat transfer and the absorption of module material radiation, the wind strength and direction, ratio of the face and rear surfaces of the module, etc. The results of the PVP operation have shown that the excess of the PV module temperature over that of the environment at high insolation values can reach 30°C. Therefore, the PV module actual temperature under operating conditions should be definitely considered. The empirical relationships obtained under actual operating conditions are used due to the complexity of theoretical determination of the module temperature. The empirical dependence of the PV module surface temperature excess  $\Delta T_{FM} = f(G, V)$  on solar radiation intensity  $G$  and wind average speed  $V$  was obtained as a result of processing of the experimental data on the silicon PV modules operation under actual operating conditions in Siberia. The resulting dependence was implemented in MatLab/Simulink as a model for calculating the PV module surface temperature according to the given values of the average wind speed  $V$ , solar radiation intensity  $G$  and ambient temperature  $T$ , as shown in Figure 2,b. Since the PV module temperature cannot change instantly due to the thermal inertia, the inertial unit implemented on the basis of the transfer function unit was included in the model.

#### 4. Calculation of the Predicted Power Output from the PVP

Consider a practical implementation of the proposed method to calculate the predicted power output from the PVP located in Tomsk (geographical coordinates 56°N, 85°E). The PVP scheme that includes the solar panel consisting of 12 PV modules of polycrystalline type JAP6-60-260 with nominal power of 260 W and the storage battery based on 12 gel lead acid batteries Delta GX 12-200 was analyzed. The initial data for simulation are the area latitude, average daily wind speed at the installation site, cloudiness level, surface albedo, number of the day of the year, azimuth and vertical angles of the solar panel installation, solar tracker type, average daily air temperature and its daily amplitude, local time of the temperature maximum, and PV module specifications. The secular trends of solar radiation intensity, diurnal air temperature range, current temperature of PV modules and their energy characteristics: short-circuit current, open-circuit voltage, fill factor, and output electric power are determined in the process of simulation. The parameters to be recorded are as follows: solar insolation value  $E$ ,  $W/m^2$ ; output power of the solar panel  $P$ ,  $W$ ; PV module and air temperature  $T$ , °C. The measured interval is one day (86 400 seconds) with a sampling interval of 1 second. The oscillograms of the recorded parameters obtained through the computational experiment that simulates the PVP operation on 20th June are shown in Figure 3.



**Figure 3.** Oscillograms of the parameters obtained through the computational experiment that simulates the PVP operation on 20th June.

## 5. Conclusion

The original simulation model of the photovoltaic power plant has been developed to simulate and investigate the plant operating modes under actual operating conditions. The proposed model considers the impact of the external climatic factors on the solar panel energy characteristics that improves accuracy in the power output prediction.

The data obtained through the PVP operation simulation enable a well-reasoned choice of the required capacity for storage devices and determination of the rational algorithms to control the energy complex. In addition, obtained results will be demanded in the study of autonomous hybrid wind-solar power systems on the basis of inverter-type diesel generator sets [12]. The use of the developed photovoltaic plant model will allow to create a fully functional simulation model of autonomous power supply system with real power equipment [13, 14].

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