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Simulation Model of Public Street Lighting Provided by a Photovoltaic Converter and Battery Storage

Martyanov A.S., Korobatov D.V., Solomin E.V.
South Ural State University
Chelyabinsk, Russian Federation
martyanov_andrey@mail.ru

***Abstract*—This paper describes a model of an autonomous public solar street lighting system powered by photovoltaic panels with energy storage battery and the lighting emission diodes consumer. The MATLAB simulating model was built for the system parameters study (voltages, currents and battery state of charge) under alternating solar intensity, photovoltaic converter efficiency and the system lighting load power. The study was focused on testing of the model under different load power conditions at the same solar power and battery charge capacity. The presented model is also used for studying the charge/discharge processes of different battery types for power plants containing solar and wind renewable sources**

Keywords—renewable energy sources; solar energy; photovoltaic converter cell panel; solar autonomous lighting; algorithms and control; MATLAB; Simulink

I. Introduction

Nowadays the systems based on the renewable energy sources, are getting wider distribution day by day [1-4]. One of the target areas for solar radiation as the most accessible renewable energy source, is photovoltaic (PV) converters [5] for powering the autonomous electricity generating power plants [6] such as public night and duty street lighting, traffic light and road sign, weather station, and environment monitoring system [7] as well as the other objects of industrial and agriculture application [8-10]. As a rule these systems are equipped with the devices storing the electric energy [11]. The charge of electro-chemical storage devices should be implemented using special algorithms developed for different battery types [12-13].

II. Street Lighting System Simulation Model

The problem of optimal components selection appears often while development of renewable based hybrid systems with electric energy storage. In most cases it is being solved with the help of different empiric methods [14-16]. The goal of the research was the development of instrument providing the suitable and demonstrable efficient analysis of quality of the component selection for reliable electric supply under some given parameters of system components. To get to the target we had to develop the simulation model of the electric supply system operating from photovoltaic converter and containing electrochemical energy source.

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For full-fledged simulation of the processes of energy conversion in the system of autonomous power supply [17] the model should enclose the models of following components:

- energy source which generates a signal proportional to the power of solar radiation, intended for simulation of daily and annual solar radiation power alteration;
- photovoltaic converter which calculates the generating electric power on the base of information about the solar radiation power;
- MPPT (Maximum Power Point Tracking) charge controller of photovoltaic converter which allows maximizing the efficiency of conversion of solar energy into electric one;
- battery which is the electrochemical storage and source of electric energy [18];
- electric load intended for the consumption of electric energy of the system.

The flowchart of electric energy conversion in the system of autonomous street lighting is shown in figure 1.

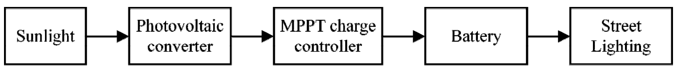

Fig. 1. Flowchart of electric energy conversion in the lighting system with photovoltaic converter

Algorithm of system operation could be presented by flowchart shown in figure 2. In the very beginning the control system determines if the photovoltaic converter is irradiated. If it is, then the current period of time is the daylight time and no lighting is required. In this case all energy generated should be delivered to the storage battery which the electric energy is stored in for further use during the dark time. If the photovoltaic converter doesn't generate electric power then it could be assumed that at that moment there is a dark time and the loading should be switched on to provide the lighting. In this case the model analyses the battery and if it has the high enough state of charge (SOC) then the control system gives the command for switching on the lighting. If the SOC is low then the lighting will be switched off until the battery will be fully charged again. The algorithm is similar to [19].

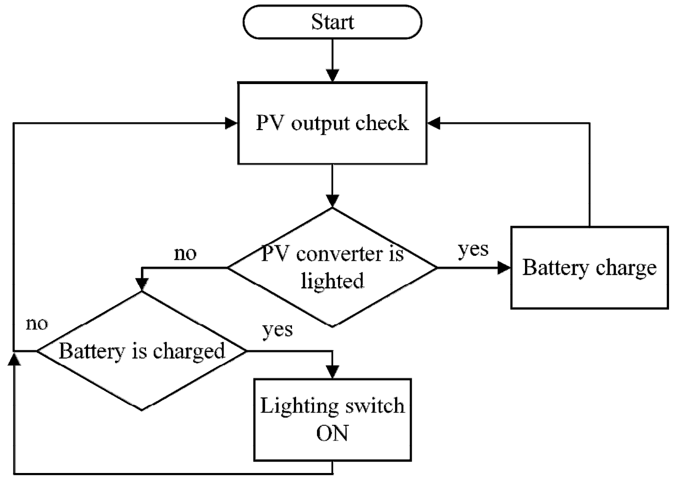

Fig. 2. Flowchart of simulating model operation

The MATLAB/Simulink environment [20] was selected for building the simulation model as widely spread among the researchers and developers of electrical systems. Simulating model was built of the following main blocks (figure 3):

“Solar source” – block simulating generated signal proportional to the power of solar radiation, intended for simulation of given daily and special annual solar radiation power alteration;

“Solar panel with MPPT controller” – block simulating the conversion of solar energy into electric one, intended for power supply of autonomous street lighting system;

“Battery with controlled load” – block providing the usage of electric energy under the programmed algorithm.

The chart also includes two secondary blocks:

“Load power” – block which reflects the power of lighting device;

“Scope” – block for visualization of modeling results.

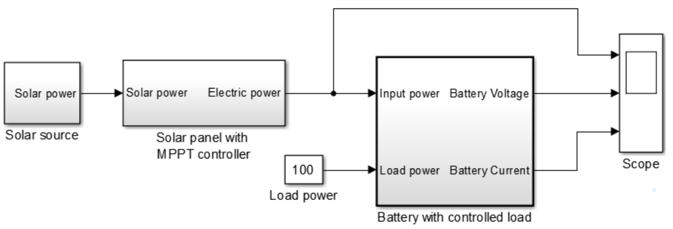

Fig. 3. Block diagram of the simulation model in MATLAB/Simulink environment

For simulating the solar radiation power alternation due to the movement of the Earth around the Sun and rotation around its axis we proposed the following model:

$$P_{sol} = A \cdot (B \cdot \sin(2\pi \cdot \omega_d) + \sin(2\pi \cdot \omega_y)) \qquad (1)$$

where P_{sol} – power of solar radiation, W/m^2; ω_d – angular velocity of Earth rotation around its axis, rad/sec; ω_y – angular velocity of Earth rotation around the Sun, rad/sec; A and B – coefficients of amplitudes selected for the appropriate geographic coordinates. Block diagram of the model is presented in figure 4.

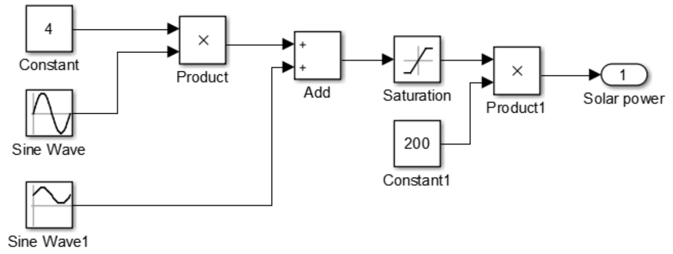

Fig. 4. Block diagram of solar radiation source in MATLAB/Simulink environment

To check the adequacy of the solar radiation source model it was tested on the short and long time intervals. The results of calculating experiments are shown in figure 5.

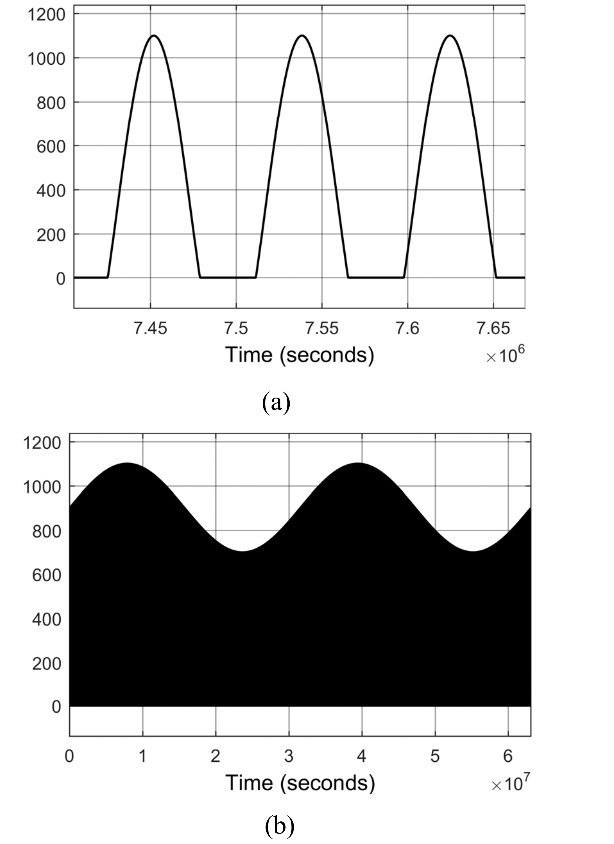

Fig. 5. Alternation of solar radiation on daily intervals (a); on yearly intervals (b).

Analyzing the presented results we could make the following conclusions:

The model simulates the alternation of solar radiation alternation during the day time. During the dark time there is no radiation power. With the increase of natural lighting the power of solar radiation is getting higher reaching the maximum on the noon, after which getting to zero simulating the sunset.

The annual alternation of solar radiation power is simulated with enough accuracy. The reduction of solar radiation power maximum could be observed during the winter time and increase during the summer. It could be noted that the proposed model simulates the duration of daylight hours. It is longer during the summer time and shorter during winter. Thus the model could be characterized as adequate for the required task solution.

The model simulating the conversion of solar power into electric one is described by the following equations:

$$\begin{aligned} P_{el} &= P_{sol} \cdot K_{eff} \\ I_{charge} &= \frac{P_{el}}{V_{bat}} \end{aligned} \qquad (2)$$

where P_{el} – electric power on the converter output, W; K_{eff} – efficiency of conversion of solar power into electric one; I_{charge} – current of storing battery charge, A; V_{bat} – voltage of storing battery, V.

"Battery with controlled load" block for simulating of algorithm of street lighting system control uses the components of Simscape library. The block diagram is shown in figure 6.

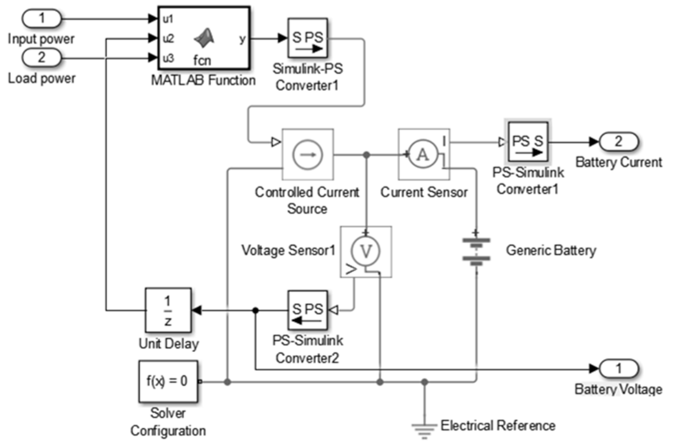

Fig. 6. Block diagram of load control system in MATLAB/Simulink

The base of the block is the "Generic Battery" model of storing battery, which condition is controlled by "Controlled Current Source" block. The task for the Controlled Current Source is being formed in "MATLAB Function" block on the base of information about the voltage of battery obtained from "Voltage Sensor1" voltmeter. The "Current Sensor" secondary block is intended for the control of current of battery charge/discharge. Algorithm of lighting system control simulated in "MATLAB Function" block is presented by the following equation system depending on the illumination and battery charge degree:

$$\begin{cases} I_{load} = \dfrac{P_{load}}{V_{bat}} \; at \; P_{el} = 0 \; and \; V_{bat} > V_{high} \\ I_{load} = 0 \; at \; P_{el} = 0 \; or \; at V_{bat} < V_{low} \end{cases} \qquad (3)$$

where I_{load} – battery load current, A; P_{load} – load power, W; V_{high} – threshold voltage of load switch off, V. Algorithm is written on MATLAB programming language. The source text of "MATLAB Function" block is shown in figure 7.

```
function y = fcn(u1, u2, u3)
% Auxiliary variable for hysteresis forming
% for threshold voltage when battery is discharged
persistent flag;
% Initializing
if isempty (flag)
    flag = 0;
end
% Prohibition of load when battery is discharged
if (u2 < 10.8)
    flag = 0;
end
% Permission of load when battery is charged
if (u2 > 12.5)
    flag = 1;
end
% Calculation of charging current when solar power
available
if (u1 > 0)
    y = u1 / u2;
% Then night. Discharge battery on lighting
elseif (flag == 1)
    % If battery is not discharged
    y = -1 * u3 / u2;
else
    % If battery is discharged
    y = 0;
end
```

Fig. 7. Source code of "MATLAB Function" block

The developed simulating computer model of street lighting system was used for study of the influence of load power on the system operability under given photovoltaic converter power and storing battery capacity. For determination of source data it was assumed that the system should contain the photovoltaic converter on 120 Watt nominal power and 55 A·h of battery capacity. The power of load was set up by numbers 50, 100 и 150 Watt.

The results of experiments are shown in figures 8-10. Figure 8 shows the results of simulating the operation of street lighting system on 50 Watt power load. The figure 8 includes three diagrams. The upper one shows the alternation of generating electric power for 3 days, the middle one shows the alternation of battery voltage and lower – the alternation of battery current.

The diagram shows that maximal electric power is 120 Watt. The voltage on the battery terminals was within 12.2…13.3 Volts, charging current didn't exceed 8 Amperes, and discharge current was 4.5 Amperes, which corresponds to the normal operation conditions of the battery. The diagrams show that during the daylight time the battery charging current is in proportion with the generated electric power. Charging current increase leads to the increase of battery voltage on terminals which could be explained by internal resistance of battery. During the dark time there is no charge and the battery current becomes negative leading to the battery discharge.

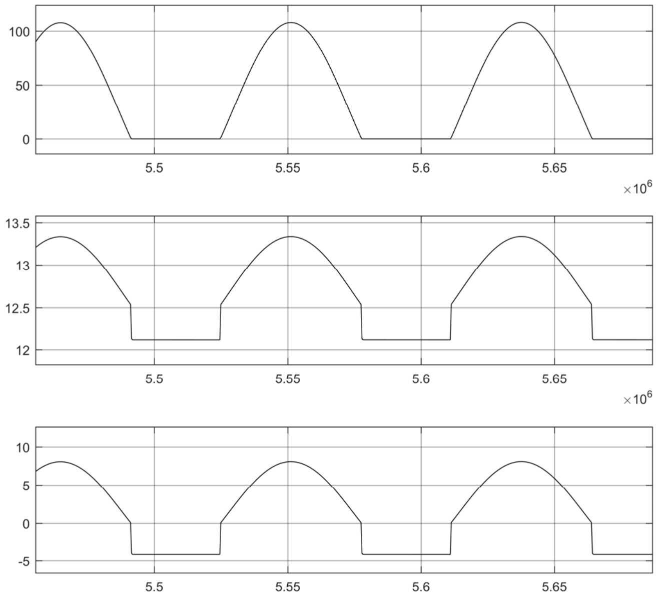

Fig. 8. Daily alternation of system parameters under 50 Watt load.

Figure 9 shows the alternation of street lighting system operation for increase of load up to 100 Watt with the same parameters of photovoltaic converter and storing battery. The diagrams of figure 9 show that on the same generating electric power the battery voltage reaches its lower threshold value 10.8 Volts, because the load current was increased to 8 Amperes. This reduction of voltage on the terminals of battery leads to the load switch off, which could be observed in the bottom diagram of figure 9. Analyzing the curves it could be noted that during the dark time when the control system has switched the lighting on, the rapid discharge is observed. It is caused by the increased battery discharge current which is in turn caused by power of lighting. The slope of battery voltage alternation curve shows that the battery state of charge getting to zero by the end of the dark time, leading to the deep discharge and reduction of voltage on battery terminals lower than the threshold. The reduction of battery voltage leads to the load switch off to avoid the excessive discharge and battery lifetime shortening. In the end of dark time the autonomous street lighting system cannot operate properly to provide lighting, i.e. becomes inoperative.

III. CONCLUSIONS

The developed simulating model of autonomous street lighting system based on photovoltaic converter of solar radiation power, is intended for demonstration of alternating the system parameters depending on the power of solar radiation, efficiency of photovoltaic converter, capacity of electric energy storing battery and power of lighting provided by the system.

The simulating model can be used for analysis of charge/discharge process in the system of electric supply from such renewable energy sources as solar and wind power.

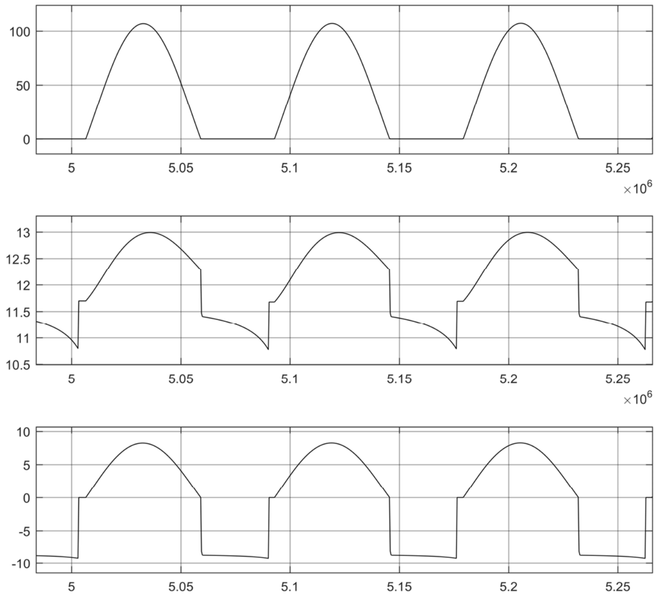

Fig. 9. Daily alternation of system parameters under 100 Watt load.

For further development of the proposed simulating model the following ways could be approached:

- making the solar power source model more complex, to simulate the influence of the weather conditions on energy work out;
- making the photovoltaic converter model more complex, to simulate different algorithms of maximum power point tracking, to maximize the generation of electric power;
- adding the battery charging controller [21] to the model for testing the influence of different algorithms of battery charge on the efficiency of accumulating and storing of electric energy in battery;
- arrangement of interaction between the objects of infrastructure of electric supply [22].

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