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Features of operation of photovoltaic plants as a supplementary source of electricity for non-traction consumers of railway electric mains

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Особливості експлуатації фотоелектричних станцій як допоміжного постачальника електричної енергії для нетягових споживачів залізничних електромереж

Мета. *Визначити особливості експлуатації фотоелектричних станцій як допоміжного постачальника електричної енергії для нетягових споживачів залізничних електромереж.*

Методика дослідження *грунтується на сучасних методах обчислювальної математики, статистики та аналізу інформації з використанням сучасних комп'ютерних технологій.*

Результати дослідження. *Авторами проведено аналіз існуючих на сьогодні передумов використання електричної енергії, яка отримана від нетрадиційних джерел (фотоелектричних станцій) для живлення нетягових споживачів залізничних електромереж. З'ясовано характер інтенсивності сонячної радіації завдяки даних метеорологічних спостережень за 2018 рік, що реєструвалися за допомогою піранометра SMP фірми KIPP&ZONEN, який спеціально розроблений для фіксації потоку сонячної енергії, що падає на плоску поверхню від сонця і небосхилу у діапазоні довжин хвиль від 300 до 3000 нанометрів (Нм), який має інтелектуальний інтерфейс, по м. Василівка Запорізької області з інтервалом* $\Delta t = 10$ *хвилин. Загальна кількість значень склала близько 25000. Отримані дані наступні: найменша інтенсивність сонячної радіації впродовж 2018 року склала 400 Вт/м^2, а найбільша – 1000 Вт/м^2. Проведено розрахунок щодо вибору фотоелектричних панелей типу PV- MLV 250 HC максимальною потужністю 250 Вт для комплектування конкретної фотоелектричної станції для встановлення в зазначеному регіоні. Авторами зроблено висновок, що для надійного енергетичного забезпечення забезпечення нетягових споживачів залізничних електромереж впродовж доби від автономних сонячних електростанцій, останні мають бути забезпечені накопичувачами електричної енергії (акумуляторними батареями) у обсягах, які перевищують необхідну навантаженню кількість приблизно у 1,7 рази.*

Наукова новизна *полягає у тому, що пропонується використання відновлюваних джерел енергії в системах електропостачання нетягових споживачів залізничного транспорту, зокрема фотоелектричних установок.*

Практичне значення. *Впровадження фотоелектричних станцій як допоміжного постачальника електричної енергії для нетягових споживачів залізничних електромереж з метою мінімізації витрат електроенергії.*

Ключові слова: *відновлювані джерела енергії, якість електричної енергії, фотоелектрична установка, мережі електропостачання залізничного транспорту, нетягові споживачі залізничних електромереж, виробництво електроенергії, інтенсивність сонячного випромінювання, акумуляторні батареї.*

Abstract.

Purpose. *To determine the features of operation of photovoltaic stations as a supplementary source of electricity for non-traction consumers of railway power grids.*

The research methodology *is based on modern methods of computational mathematics, statistics and information analysis using modern computer technology.*

Findings. *The authors analyze the current prerequisites for the use of electricity obtained from non-traditional sources (photovoltaic stations) to supply non-traction consumers of railway power grids. The nature of the intensity of solar radiation was clarified due to meteorological observations for 2018, recorded using a SMIR pyranometer from KIRP & ZONEN, which is specially designed to record the flow of solar energy falling on a flat surface from the sun and sky in the wavelength range from 300 to 3000 nanometers (Nm), which has an intelligent interface, in the city of Vasylivka, Zaporizhia region with an interval of minutes. The total number of values was about 25,000. The data obtained are as follows: the lowest intensity of solar radiation during 2018 was 400 W / m^2, and the highest - 1000 W / m^2. The calculation of the choice of photovoltaic panels type PV-MLV 250 NS with a maximum power of 250 W for the completion of a specific photovoltaic station for installation in the specified region. The authors conclude that in order to provide reliable energy supply to non-traction consumers of railway power grids during the day from autonomous solar power plants, the latter must be provided with electricity (storage batteries) in quantities exceeding the required load by about 1.7 times.*

The originality *is that the use of renewable energy sources in the power supply systems of non-traction consumers of railway transport, in particular photovoltaic installations, is proposed.*

Practical implications. *Introduction of photovoltaic stations as a supplementary source of electricity for non-traction consumers of railway power grids in order to minimize electricity costs.*

Keywords: *renewable energy sources, quality of electric energy, photovoltaic plant, power supply networks of railway transport, non-traction consumers of railway electric networks, electricity production, solar radiation intensity, storage batteries.*

Introduction

Currently, non-traditional power sources occupy an increasing volume in the energy market in Ukraine, namely bioenergy, heat pumps, geothermal heat, solar energy, small hydropower. Now renewable energy sources are developing rapidly, the number of suppliers is increasing and the conditions for providing electricity supply services are changing [1, 2]. Over the past few years, Ukraine has made significant progress in the development of renewable energy sources, namely solar and wind power plants. Regarding the possibilities of using unconventional energy in the power supply systems of non-traction consumers of railway power grids shows several possible areas: 1)

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power supply system from the external power system, which, along with traditional, operate in parallel and renewable energy sources; 2) use of renewable energy to supply infrastructure [3] and consumers' own needs [4]. Particular attention is paid to areas where the external electricity supply of railways is unstable, so the use of renewable energy sources to meet the needs of non-traction consumers is an important task.

Analysis of literature sources and problem statement

Scientific and practical developments on the introduction of renewable energy systems in the railway power grid have been studied in many works of Ukrainian [5-7] and foreign [8-11] scientists. Areas of application of renewable energy sources in railway power grids can be autonomous objects of railway transport infrastructure, sources of external lighting and other non-traction consumers.

The purpose and objectives of research

In each specific case, efficiency of PVP use in the power supply systems of non-traction consumers is identified by means of climatic and meteorological conditions of the area where they are planned to be mounted. Hence, PV plants should follow after previous energy evaluation of solar radiation which helps support expediency of such an extra source.

Solar radiation intensity, which defines energy amount falling on a measurement unit of land surface area for a single time period, is of random nature like wind flow energy. Thus, the electric energy, generated by photovoltaic plants at any time is of unpredictable amount too.

Like in case with WPP, capacity of photovoltaic battery (PVB) is limited by a specific value, so-called nominal (rated) capacity P_{nom}^{FVB} which remains constant after solar radiation intensity achieves its nominal values. To support the fact, Fig. 1 demonstrates the experimental dependences of a photomodule capacity upon the mentioned intensity in terms of voltage invariance on its clamps.

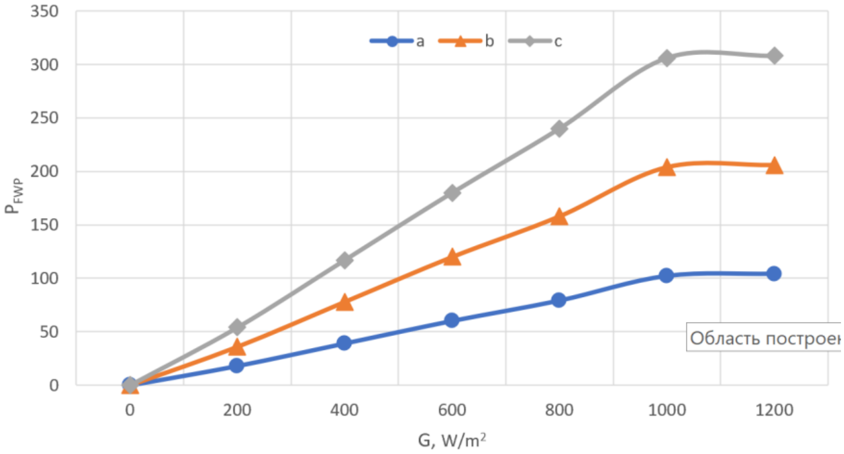

Fig. 1. Experimental dependences of the photomodule capacity dependence upon the solar radiation intensity when voltage on clamps is 12V (a), 24V (b), and 36V (c)

Paper [12] determines a dependence of photovoltaic battery capacity within $0 \div G_{nom}$ interval using the equation

$$P_{FVP} = \eta_{FVP} \cdot F_{FVP} \cdot G_t = \eta_n \cdot \eta_{CU} \cdot [1-\beta \cdot (T_C - T_{RT})] \cdot A_{FVP} \cdot G_t, \quad (1)$$

where G is solar radiation intensity, W/m^2;

η_{FVP} is battery efficiency factor;

η_n is rated photomodule efficiency;

η_{CU} is capacity use efficiency;

β is temperature efficiency coefficient;

T_{RT} is the rated temperature of photocells, ^{0}C; and

T_C is the current photocell temperature, ^{0}C.

The latter is identified as follows:

$$T_C = T_{AT} \cdot \left(\frac{T_{nom}}{800}\right) \cdot G_\tau, \quad (2)$$

where T_{AT} is ambient temperature, ^{0}C; and

T_{nom} is nominal photocell temperature, ^{0}C.

Efficiency of the use of capacity, when it achieves the last maximum value, is $\eta_{CU} = 1$. As for the temperature efficiency coefficient, it is considered as the virtually unchanged one for the specific semiconductor type. For instance, it is $\beta = 0.004 \div 0.006\ ^0C^{-1}$ for silicon photocells.

Taking into consideration the fact that $\eta_{CU}, \beta, T_{nom}$ *and* F_{FVP} are technical parameters of PVP, specified by their manufacturer, temperature and solar radiation intensity remain independent random values in terms of equation (1). The abovementioned verifies linear nature of the obtained dependences of the output capacity upon intensity of the latter within $G = 200 \div 1000$ W/m^2 interval.

Advantages of model (1) are as follows: it takes into consideration influence of environmental temperature and photomodule temperature making it possible to simulate PVB-based generating stations. However, it cannot demonstrate dependence of the plant capacity upon the voltage on its clamps, and intensity of current consumption despite the fact that the last ones are among the key parameters of any photovoltaic panel.

Thus, solution of relevant practical problems more often applies a dependence, although simplified one, named as a model of ideal photocell [13,14]. It corresponds to the most popular and easy to implement one-diode photocell replacement circuit (Fig. 2) consisting of photocurrent source (I_{FC}), diode (D), shunt resistor (R_{Sh}), and resistor simulating internal series cell resistance (R_{ISR}).

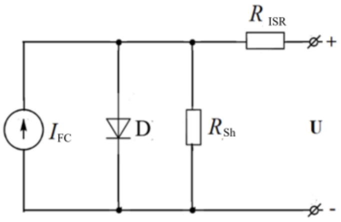

Fig. 2 Equivalent circuit of a photocell replacement

The mentioned, more widely used dependence of a photocell capacity is

$$P_{FVB} = U_{FVB}\left\{G\cdot[I_{SC}+K_I\cdot(T-T_{RT})]-I_D\cdot(\exp\frac{q\cdot U_{FVB}}{K\cdot T\cdot A})-I\right\},\quad(3)$$

where U_{FVB} is voltage across a photocell, B;

I_{SC} is short circuit current of a photocell, A;

K_I is temperature coefficient of short circuit current;

T is operating temperature of a photocell, ^{0}K;

T_{RT} is rated temperature of photocells, ^{0}K;

I_D is reverse saturation current of a diode, A;

$q = 1.6\cdot10^{-19}$ Coulomb is electron charge;

$K = 1.38\cdot10^{-23}$ J/^{0}K is Boltzmann constant;

A is coefficient of the photocell ideality determined by means of its manufacturing method; and

I is current consumed, A.

Despite the fact that the equivalent models and (3) dependence are considered as the ideal one, they should be related to a load value and nature to evaluate the photocell influence on the operation of the whole energy power supply system. That will make it possible to calculate the amount of the generated electric energy and evaluate efficiency of its use.

It is possible to identify the amount of electric energy, generated by means of photovoltaic conversion, with (3) dependence using the expression

$$W_{FVP} = \tau_{FVP}\cdot U_{FVP}\left\{G\cdot[I_{SC}+K_I\cdot(T-T_{RT})]-I_D\cdot(\exp\frac{q\cdot U_{FVB}}{K\cdot T\cdot A})-I\right\},\quad(4)$$

where τ_{FVP} is period of photovoltaic device operation, hours.

The equation describes a process of electric energy generation by means of a photovoltaic device under the specific conditions: solar radiation intensity (G), photocell temperature (T), and period of solar energy transformation into electric one (τ_{FVP}).

Identify the intensity nature of solar intensity relying upon the meteorological observation data of 2018. They were recorded with the help of a sensor, mentioned in Chapter 4.3, in the town of Vasylivka, Zaporizhzhia Oblast, with $\Delta t = 10$ min interval. The total amount of values is almost 25000. It has been determined that in terms of the terrain, length of day varies from 7 hours in December to 15 hours in June, i.e. 3.5 and 7.5 hours respectively on either side relative to the current value being 11.5 hours.

During the mentioned year, minimum solar radiation intensity was 400 W/m^2, and maximum value was 1000 W/m^2. In this context, if intensity fluctuations are considered within 8-10% from the last value, then such its value is available during April-August. Unfortunately, it depends heavily upon cloudiness, and may decrease down to the same 400 W/m^2 or even less. Fig. 3 demonstrates fragments of the fluctuations.

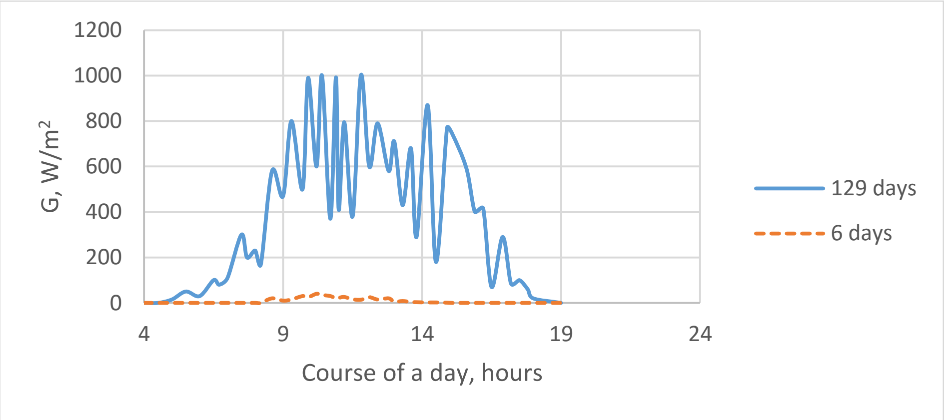

Fig. 3. Intake of solar radiation during a day in May (a) and a day in January (b) in 2018 (town of Vasylivka, Zaporizhzhia Oblast)

Thus, cloudiness complicates considerably electric energy generation by FVP. The matter is that average daily intensity may experience more than twofold decrease from 1000 W/m^2 on sunny days down to the same 400 W/m^2. As for the distribution of the experimental data being considered, their histogram (Fig. 4) stores almost constant $300 \div 900$ W/m^2 intensity value.

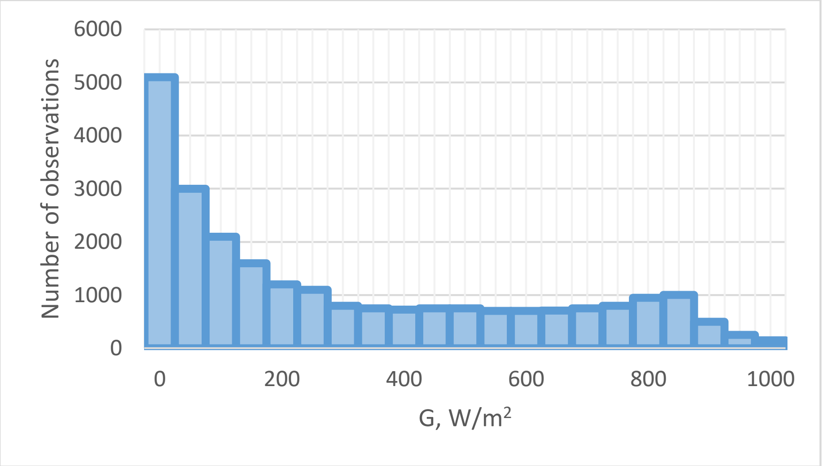

Fig. 4. Histogram of experimental data distribution as for the solar intensity distribution in 2018 (town of Vasylivka, Zaporizhzhia Region)

The analysis supports the idea that while using FVP as the autonomous supply source of the specific non-traction consumers (i.e. their disconnection from the mains), it is required to select capacity of a photovoltaic station in terms of the solar radiation intensity in November-January. In this context, summer will demonstrate significant excess of the generated electricity which should be lost or used in some way. Like in the case with WPP application, a buffer SB has to be available. The battery will smooth out fluctuations in energy generation or even its lack at night, within 24 hours.

As it has been determined in the previous chapter, the energy, accumulated by SB, excess in the amount of daily consumption should be more than 1.7 times. Consequently, 60 kW·h consumption should involve such storage battery which can accumulate 104 kW·h of electric energy. For instance, if voltage is 12V, its energy intensity should be 8708 33 A·h.

It is also important to bear in mind that it is possible to charge the SB (as it is known by [15]) if only output capacity of a power source, being PVS in this case, is more than the mentioned 12 V. That is why, selection of the type of photopanels, their amount, and connection diagrams should involve the nuances as well.

Consider use of photovoltaic panel of PV- MLV 250 HC type which specifications are listed in Table 1 [16]. Dependences of output voltage of the photovoltaic panel upon the solar radiation intensity, obtained with the help of the abovementioned experimental setup, are in Fig. 5.

Table 1

Specifications of photovoltaic panel of PV- MLU250HC type

	Parameter	Value
1	Cell type	Monocrystalline silicon
2	Cell dimensions, mm	78×156
3	Number of cells within one panel, pieces	120
4	Maximum capacity, W	250
5	Guaranteed minimum value of maximum power, W	242.5
6	Idle voltage, V	37.6
7	Short circuit current, A	8.79
8	Voltage in terms of maximum capacity, V	31
9	Current in terms of maximum capacity, A	8.08
10	Efficiency, %	15.1
11	Tolerable deviations of maximum capacity, %	±3
12	Normal operating cell temperature, °C	45.7
13	Maximum voltage of the system, V	600
14	Cut out current, A	15
15	Overall dimensions, mm	1625×1019×46
16	Weight, kg	20

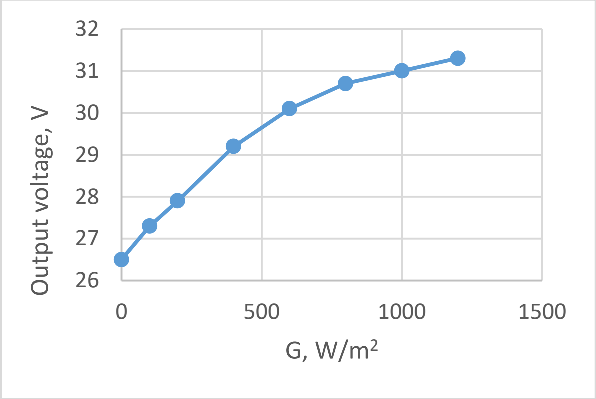

Fig. 5. Dependence of the output voltage of PV-MLU250HC photovoltaic panel upon solar radiation intensity

In terms of the considered example, the last conditions will be met since output PVS voltage is not less than 12 V required for SB. Hence, at radiation intensity, corresponding to April-August (almost 1000 W/m^2) when output voltage of the panels is 31 V it will become possible to connect in series no more than two storage batteries. That is quite sufficient even in winter since in terms of 29 V voltage of one panel the mentioned number of batteries will provide the total 24 V value.

As for the total number of PV panels within a photovoltaic station, required to supply consumer with 60 kW capacity in summer, it is quite understood that in terms of 235 W (Fig. 6) by one panel, there will be necessary to connect in parallel 255 pieces. In winter, when unit capacity of PV panel drops down to 75 W, the station should involve 800 mentioned panels.

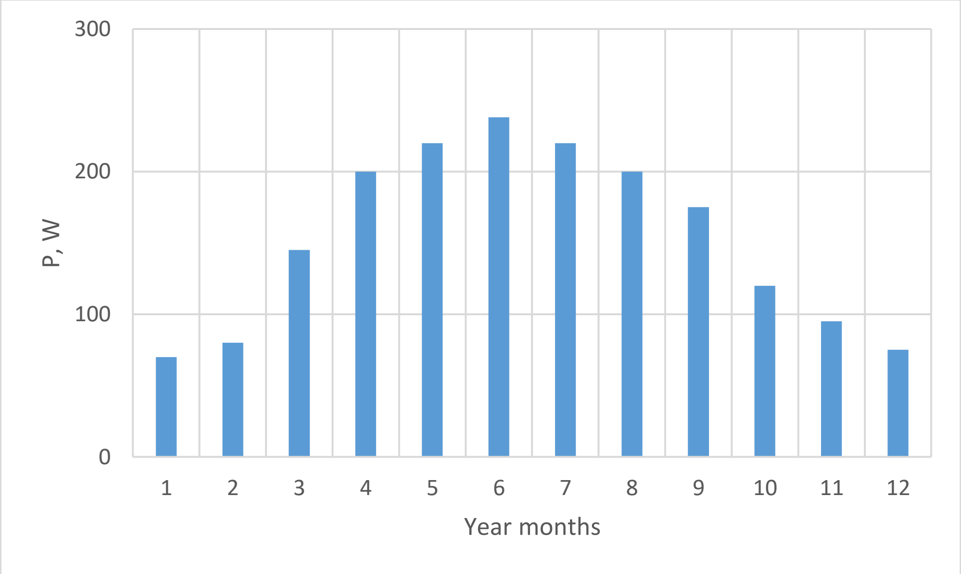

Fig. 6. Distribution of the average monthly capacity of PV panel of PV-MLU250HC type located in town of Vasylivka, Zaporizhzhia Oblast during 2018

Conclusion

Minimum and maximum solar radiation intensity has been identified within the mentioned Ukrainian regions in terms of seasons. The values are almost 400 W/m^2 and 1000 W/m^2 respectively. Unfortunately, they depend heavily upon the cloudiness thus decreasing even during a summer day down to a winter 400 W/m^2 value. The fact complicates considerably the electricity generation by PVP.

To guarantee power supply of non-traction consumers during 24 hours, the electricity, generated by the autonomous wind turbines and solar power plants, should be accumulated in the amounts, 1.7 times exceeding the amount corresponding to load.

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