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# DEVELOPING ELECTRICAL MODELS TO SIMULATE THE CONVERSION OF SOLAR RADIATION INTO ELECTRICAL AND THERMAL ENERGY

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***Abstract.*** *This article focuses on developing electrical models to investigate the conversion of solar radiation into both electrical and thermal energy. Our findings indicate that semiconductor converters are unable to harness the entire electromagnetic spectrum emitted by the sun. A substantial portion of solar radiation is transformed into heat. To achieve these results, we employed a corpuscular model to represent the solar radiation flow and a quantum mechanical framework to describe the energy associated with electromagnetic radiation and thermal processes within the crystal. To derive electrical modeling parameters, this study leveraged the principle of electrical and electrothermal analogies. We established a direct equivalence between the flow of solar photons and the flow of charge carriers represented by the electric current. Additionally, we demonstrated that the energy carried by photons is analogous to the voltage generated across the photovoltaic device. When modeling thermal energy using electrical circuits, we found that the electric current can be used to represent the flow of phonons, quasiparticles associated with thermal vibrations in the crystal, while the voltage corresponds to the energy of phonons. This study developed electrical models to simulate the conversion of solar radiation into both electrical and thermal energy. Current and voltage sources were employed to represent the energy conversion processes. It is shown that the internal resistances of energy sources in electrical models simulate the losses during the generation of electrical and thermal energy. It is noted that the proposed electrical model of a photovoltaic power source corresponds to the traditional equivalent circuit with a diode. The paper concludes by discussing the potential applications of the proposed modeling framework.*

***Keywords:*** *electrical model, solar radiation, electrical energy, thermal energy, analogies, photon, phonon*

# СТВОРЕННЯ ЕЛЕКТРИЧНИХ МОДЕЛЕЙ ДЛЯ МОДЕЛЮВАННЯ ПРОЦЕСІВ ПЕРЕТВОРЕННЯ СОНЯЧНОГО ВИПРОМІНЕННЯ НА ЕЛЕКТРИЧНУ І ТЕПЛОВУ ЕНЕРГІЇ

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***Анотація.*** *Стаття присвячена побудові електричних моделей для дослідження процесів перетворення енергії сонячного випромінювання на електричну і теплову енергії. В роботі показано, що не весь спектр електромагнітного випромінювання Сонця перетворюється в напівпровідниковому перетворювачі на електричну енергію. Значна частина сонячного випромінювання перетворюється на теплову енергію. В статті було використано корпускулярне представлення потоку сонячного випромінювання та квантово-механічне представлення енергії електромагнітного випромінювання та енергії теплових процесів у кристалі. Для отримання електричних моделювальних величин у роботі було застосовано принцип електричних та електротеплових аналогій. Було показано відповідність потоку частинок сонячного електромагнітного випромінювання, фотонів, потоку згенерованих носіїв заряду, тобто струму. Також було показано, що енергія фотонів відповідає напрузі, яка створюється на електродах фотоелектричного перетворювача. В роботі показано, що в разі моделювання теплової енергії за допомогою електричних моделей струм моделює* *потік квазічастинок теплових коливальних процесів у кристалі, фононів, а енергія фононів моделюється напругою.*

*У роботі були побудовані електричні моделі процесу перетворення сонячного випромінювання на електричну енергію та процесу перетворення сонячного випромінювання на теплову енергію. При цьому було використано джерело струму та джерело напруги, які саме й моделюють процеси перетворення однієї енергії на іншу. Показано, що внутрішні опори джерел енергії в електричних моделях моделюють втрати при генерації електричної та теплової енергії. Відмічено, що запропонована в роботі електрична модель фотовольтаїчного джерела електричної енергії відповідає традиційній еквівалентній схемі з діодом. Були зроблені висновки та показано область застосування запропонованих принципів та моделей.*

***Ключові слова:*** *електрична модель, сонячне випромінювання, електрична енергія, теплова енергія, аналогії, фотон, фонон.*

**Introduction.** The widespread use of solar energy has highlighted the need for comprehensive modeling of various solar energy systems, such as centralized and distributed systems [1]. As a result, there is a growing demand for research into different applications of solar radiation [2]. A fundamental aspect of this research is the detailed study of solar radiation characteristics.

For the calculation, modeling, and analysis of solar energy systems, a thorough understanding of the processes involved in converting the electromagnetic energy of solar radiation into electrical and thermal energy is essential. Classically, electromagnetic energy is carried by waves, whereas in quantum mechanics, it is carried by photons.

Developing models of solar radiation energy carriers is an effective and practical approach to conducting such research. Given that electrical energy is the most efficient end product of electromagnetic energy conversion, the use of electrical models of absorption, emission, and conversion processes of electromagnetic waves or photons is highly effective.

To create effective electrical models, it is recommended to employ electrical analogy methods [3] that establish correspondences between fundamental physical quantities and electrical parameters.

**Objective of the work.** To develop electrical models of the processes of converting solar radiation into electrical and thermal energy based on electrical analogy methods and the corpuscular nature of light and heat.

**Materials and methods**

***Spectrum and energy.*** The electromagnetic energy flux incident on Earth from the Sun exhibits a distinct spectral distribution, and a substantial fraction of this spectrum can be transformed into electrical energy via the photovoltaic effect in semiconductors. Nevertheless, due to the mismatch between the absorption spectrum of solar radiation in semiconductor photovoltaic devices and the spectrum of the conversion of radiation energy into electrical energy (Fig. 1) [4], the development of electrical models for the processes of solar radiation conversion into both electrical and thermal energy is imperative.

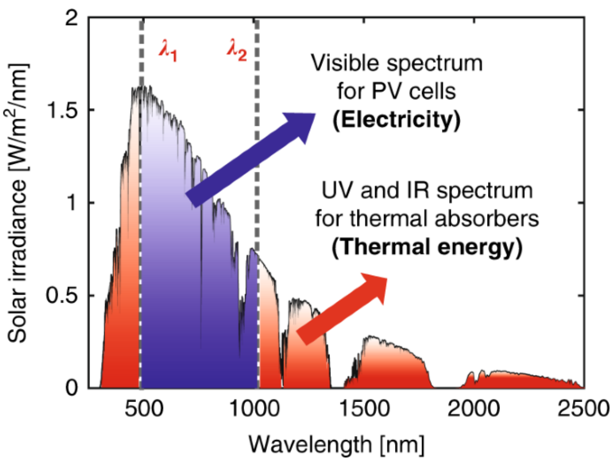


*Fig. 1. Spectrum of solar radiation*

When considering the classical interpretation of solar radiation, the electric and magnetic field intensities are not particularly suitable for model development due to the lack of corresponding quantities in circuit theory. However, according to quantum theory, solar radiation consists of photons, and the energy of each photon is given by the formula [5, 6]:

$$E_{ph} = h\nu, \quad (1)$$

where $E_{ph}$ – energy of photon, *h* – Plank's constant; $\nu$ – frequency of photon.

Quantum theory views light as consisting of particles –photons – which aligns well with the particle-based nature of electrical circuits (where electrons are the charge carriers). Hence, when creating electrical models, photons can be directly analogous to electrical charge carriers (p -> e). This analogy can be extended to thermal processes as well.

The number of photons incident on a semiconductor per unit time is essentially the light intensity or luminous flux, as it is directly proportional to the number of photons. Therefore, the energy of a monochromatic photon flux is:

$$E_{ph\_flow} = nh\nu, \quad (2)$$

where *n* – number of particles.

The main energy transition responsible for the photovoltaic effect in semiconductors involves the absorption of quanta, causing electrons to be excited from the valence band $E_V$ to the conduction band $E_C$. This intrinsic light absorption generates both free electrons and holes. For such transitions to occur, the photon energy must exceed the bandgap energy $hv \geq \Delta E$, where $\Delta E$ represents the energy required to excite the intrinsic atoms of the semiconductor. Impurity levels also play a role in the absorption process. The excitation of donor and acceptor impurities requires photon energies of $hv \geq \Delta E_d$ and $hv \geq \Delta E_a$, respectively, where $\Delta E_d$ and $\Delta E_a$ are the excitation energies of donor and acceptor atoms. Furthermore, other non-main energy transitions within the crystal can occur.

***Electricity.*** If every absorbed photon has a probability of generating a free charge carrier or an electron-hole pair, then the rate at which charge carriers are generated is directly proportional to the photon flux. Consequently, a direct correlation exists between the electrical current and the photon flux:

$$\frac{d(n_{ph})}{dt} \to \frac{d(n_e)}{dt}, \quad (3)$$

where $n_{ph}$ – number of photons; $n_e$ – number of electrons

By introducing the elementary charge $e$, we can formulate an expression for the integrated power associated with the photon flux:

$$\eta P_{ph\_flow} = P_{e\_flow} = \frac{hvn}{t}\frac{e}{e}, \quad (4)$$

where $P_{ph\_flow}$ – power of photon flux; $P_{e\_flow}$ – power of charge flux; $\eta$ – efficiency of conversation photons to electricity; $e$ – elementary charge.

Electrically, power $P$ is expressed as the product of current $I$ and voltage $U$:

$$P = IU. \quad (5)$$

Comparing equations (4), (5), and (3), it is evident that

$$\frac{ne}{t} \to I, \quad (6)$$

and

$$\frac{hv}{e} \to U. \quad (7)$$

***Heat.*** Thermal energy arises when excess or insufficient photon energy, incident upon a semiconductor, is absorbed by the solid's crystalline structure. Atoms in a solid are in constant motion, with the amplitude of their oscillations around the lattice points increasing with temperature. According to quantum theory, an atom can only change its energy in discrete quanta. Consequently, the energy of an atom is quantized, changing in discrete portions, and the magnitude of these energy portions, similar to photons, is determined by formula (1), where $f$ is the frequency of atomic oscillation. The quantization of energy absorption by an atom significantly influences both the motion of individual atoms and the overall state of the solid. Waves are formed within the solid. Since any wave can be considered as a stream of quanta, thermal vibrations in a solid consist of quasiparticles of lattice vibrations – phonons [7].

A phonon, like any quantum, possesses energy $\Delta E_{pn} = hf$. If a crystal consists of $m$ unit cells, then the energy flux of the total number of phonons will be

$$E_{pn\_flow} = mhf, \quad (8)$$

where $m$ is the number of phonons; $f$ is the vibrational frequency of atoms in the crystal lattice.

Given the above, a direct correlation exists between the thermal energy and the photon flux:

$$\frac{d(n_{ph})}{dt} \to \frac{d(n_{pn})}{dt}, \quad (9)$$

where $n_{ph}$ – number of photons; $n_{pn}$ – number of phonons.

By introducing the quasi-particle of entropy $s$, we can formulate an expression for the integrated power associated with the photon flux:

$$(1-\eta)P_{ph\_flow} = P_{pn\_flow} = \frac{hfm}{t}\frac{s}{s}, \quad (10)$$

where $P_{pn\_flow}$ – power of phonon flux; $s$ – quanta of entropy.

Comparing equations (9), (10), and expression of electric power (5), it is evident that

$$\frac{ms}{t} \to I_{pn}, \quad (11)$$

and

$$\frac{hf}{s} \to U_{pn}. \quad (12)$$

**Results.** Using the derived relationships, we can develop electrical models to simulate the processes of converting solar radiation into electricity and heat.

From relations (6) and (7), we can see that the presence of a certain number of photons being converted into charge carriers is modeled by a current source, while the energy of the photons required for absorption during the creation of an electron-hole pair is modeled by a voltage source. Thus, the electrical model of the charge carrier generation process is a current source with an internal resistance, while the electrical model of the potential difference creation across the photocell electrodes is a voltage source with a certain internal resistance. Therefore, the electrical model of the photon conversion processes into electron-hole pairs can be represented as shown in Fig. 2.

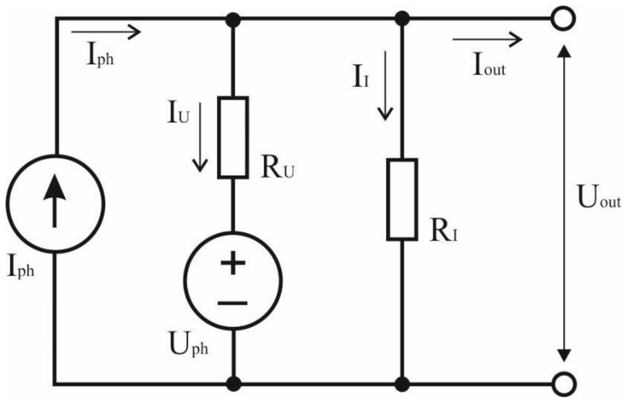


*Fig. 2. Electric model of photon-electricity conversation in PV cell*

As seen in Figure 2, the voltage source $U_{ph}$ and resistance $R_U$ correspond to the linearized equivalent circuit of a diode [8]. Therefore, the electrical model in Figure 2 can be simplified to the classic equivalent circuit of a photovoltaic cell as shown in Fig. 3 [9].

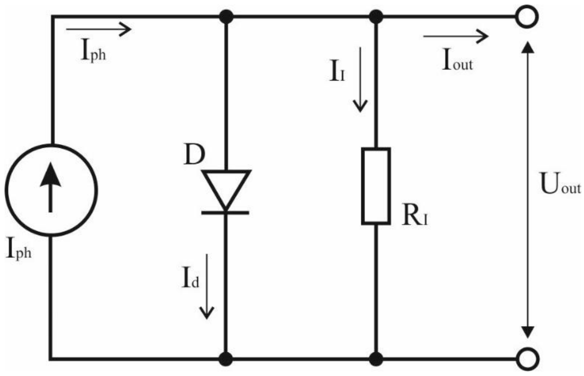


*Fig. 3. Electric model of PV cell*

The internal resistance of the current source RI in Fig. 2 and 3 models various physical processes of photon and charge carrier losses, and can consist of a group of parallel resistors modeling losses due to reflection and shading, photon absorption in the semiconductor without the generation of electron-hole pairs, scattering on lattice vibrations, and recombination of generated charge carriers at defects [10].

On the other hand, according to the electrical model in Fig. 2, the voltage $U_{ph}$ generated during photogeneration is determined by the energy barriers within the semiconductor. The electromotive force of the voltage source represents the bandgap, while the voltage drop across the internal resistance $R_U$ accounts for the effects of impurities, temperature, and other semiconductor properties that reduce the potential barrier for electron-hole pair formation [11, 12].

Electrical equations of a photovoltaic source from Fig. 2 are

$$I_{out} = I_{ph} + I_U + I_I, \quad (13)$$

$$U_{out} = U_{ph} + U_{Ru}, \quad (14)$$

$$U_{Ru} = I_U R_U, \quad (15)$$

where $I_{ph}$ – current of photon-charge conversion; $I_I$ – current in internal resistivity of current source; $I_U$ – current of voltage source; $I_{out}$ – output current of a PV-source; $R_U$ – internal resistivity of current source; $U_{ph}$ – voltage on photon-charge conversion; $U_{Ru}$ – voltage on internal resistivity of voltage source; $U_{out}$ – output voltage of a PV-source.

The current $I_U$ could give by the standard diode theory (Shockley diode equation) [13]:

$$I_U = I_d = I_0 \left( e^{\frac{eU_{out}}{kT}} - 1 \right), \quad (16)$$

where $I_d$ – current of diode; $I_0$ – saturation current; $k$ – Boltzmann's constant; $T$ – cell temperature [14].

Considering equations (11) and (12), we see that a certain number of photons are converted into phonons, and this process is modeled by a current source, while the energy of the photons transferred to the crystal lattice is modeled by a voltage source. Thus, the electrical model of the heat generation process, namely the entropy flow, is a current source, and the electrical model of the temperature difference creation between the absorbing element and the external environment is a voltage source with a certain internal resistance (Fig. 4).

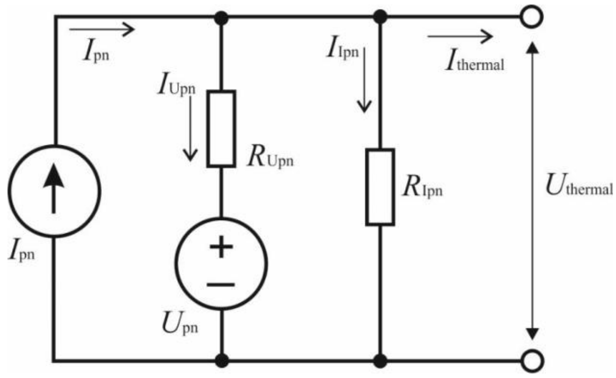


*Fig. 4. Electric model of photon-heat conversion in PV cell*

The resistance $R_{Ipn}$ in Fig. 4 models various physical processes of phonon losses and can consist of a group of parallel resistors modeling phonon losses due to useless heat radiation, photon absorption in the semiconductor without phonon generation, and phonon losses due to useless convective heat losses [15, 16].

On the other hand, the processes of obtaining a temperature difference and, consequently, a model voltage during heat generation, according to the electrical model (Fig.4), also depend on the energy of photons. Specifically, the model electromotive force of the voltage source in Fig.4 is formed from the frequency of phonons, which is transferred to the frequency of vibrations of the crystal lattice cells. Such voltage can have a certain spectrum of values, since the photons falling on the photocell and the lattice vibrations are not monochromatic. The decrease in voltage in this electrical model resulting from internal resistance, occurs due to dissipative processes in the crystal lattice of the solid (photocell) [17].

**Conclusion.** Our findings demonstrate that electrical models can be effectively developed for both electrical and thermal processes in solar photovoltaic and thermal generating elements by utilizing analogy principles and analyzing the corpuscular nature of solar energy conversion.

In this work, electrical models were developed for photovoltaic and thermal generation based on quantum processes of solar radiation absorption. In constructing the electrical model of thermal generation, quantum processes for the formation of quasiparticles such as phonons – quanta of vibrational processes within a crystal lattice, i.e., the processes of generation and propagation of thermal energy – were taken as a basis.

The transition from photon energy to the voltage generated by a photovoltaic cell and the transition from photon flow to the electrical current generated by a PV cell are natural and fully describe the conversion processes. It is shown that the resulting electrical model corresponds to the traditional equivalent circuit with a diode. It was also established that the modeled energy of phonons, formed by the absorption of photons that do not participate in electrical generation, corresponds to the modelled voltage, and the modelled entropy flow of phonons, under the same conditions, corresponds to the modelled current of the electrical model's power source.

An effective example of the application of the theory presented in this article is the calculation of solar hybrid PVT collectors, which combine the generation of electrical and thermal energy [18]. Given that cogeneration hybrid energy equipment is a complex system, for example, with coolant pumping devices, pumps that require electrical power [19], and includes mutual influence between the electrical and thermal subsystems, the approach described above allows for the analysis, research, and simulation of the entire energy system. In addition, small, unified generating devices can be combined into larger systems [20], so a convenient modeling method, such as the one proposed in the article, allows for quick calculation of scalable generating systems and energy clusters.

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