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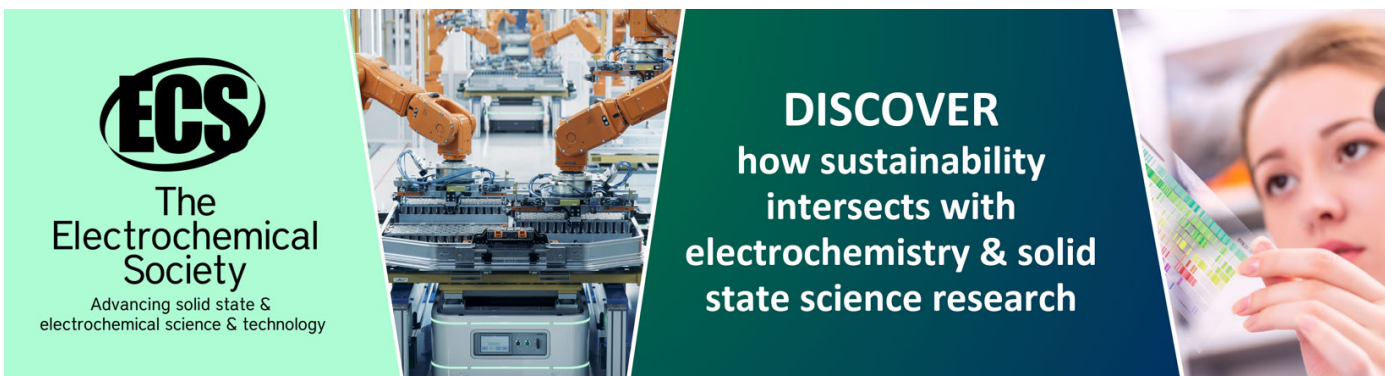
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# Study of the energy parameters of the system “solar panels – solar inverter – electric network”

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**Abstract.** The article presents the results of research into the process of transferring electrical energy from solar panels through a hybrid solar inverter to a three-phase electrical network. An automatic regulation system is presented, which provides power regulation and operation in the mode of maximum power selection from solar panels. The results of the study of the energy efficiency of the system, the parameters of electromagnetic compatibility and the emission of higher harmonic currents are presented.

## 1. Introduction

The generation and consumption of electricity in the world is constantly growing. At the same time, the generation of electricity from alternative energy sources, including solar photovoltaic panels (PV), is also growing rapidly [1,2].

In 2020 total electrical power generation of all solar panels was about 760 GWh, what is approximately 3% of the world's total electricity. At the same time, the total amount of solar energy that the Earth receives from the sun per year is  $174 \cdot 10^{14}$  PWh, which indicates significant reserves of the possibility of solar generation [3,4].

The conversion of sunlight into electric current with the help of the photoelectric effect, which occurs in solar photovoltaic cells. The first solar photovoltaic cell was invented by the American scientist Charles Fritts back in the 1880. The first industrially produced solar cell was developed in 1931 by the German engineer Bruto Lange. However, the efficiency of such a solar element was approximately 1%. Since then, the parameters of solar panels have been constantly improving.

Monocrystalline solar panels, polycrystalline solar panels and thin-film solar cells are widely used today. The most important parameters of solar panels are their efficiency and cost. Polycrystalline solar panels have an efficiency of 15.5-18%, and monocrystalline solar panels have an efficiency of 18.5 to 23.5%. However, monocrystalline solar panels have a higher cost, which is due to the fact that monocrystalline panels use monocrystalline silicon with a very high degree of purification above 99.99% [5,6].

Today, some experimental samples of solar panels have an efficiency above 47%. In 2013, Sharp created a three-layer 4×4 mm indium-gallium-arsenide photocell with an efficiency of 44.4%. Another way to increase the efficiency of solar panels is the use of additional lenses.



Thus, a group of specialists from the Institute of Solar Energy Systems of the Fraunhofer Society, the companies Soitec, CEA-Leti and the Berlin Helmholtz Center created solar panels using a Fresnel lens, a photocell with an efficiency of 44.7%.

In 2014, the Fraunhofer Institute for Solar Energy Systems created solar cells in which, thanks to a lens focusing light on a very small photocell, the efficiency is 45%. Therefore, the prices of such solar cells are an order of magnitude higher. A promising direction is the creation of nanoantenna-based photocells that work on the direct rectification of currents induced in the antenna of small sizes (about 200-300 nm) by light (that is, electromagnetic radiation of a frequency of about 500 THz). Nanoantennas do not require expensive raw materials for production and have a potential efficiency of up to 85%. But this technology is not yet ready for serial production [7, 8].

The purpose of the study is to obtain scientific results of the process of transferring electrical energy from solar panels through a hybrid solar inverter to a three-phase electrical network. To achieve the purpose, the following objectives were set:

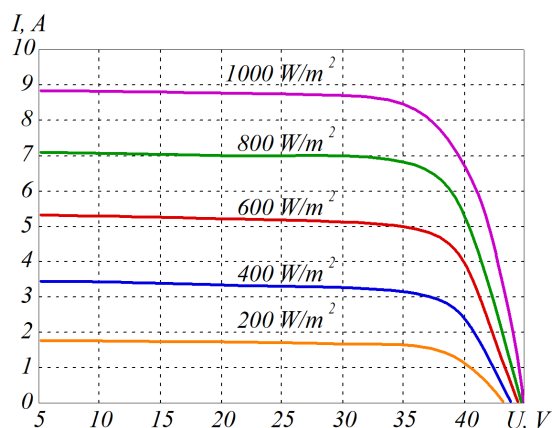
- to develop a simulation model of a system for generating electricity from solar panels to a general industrial network using a solar inverter;
- investigate transients in the electrical network and solar panel when starting the converter.

## 2. Results and discussion

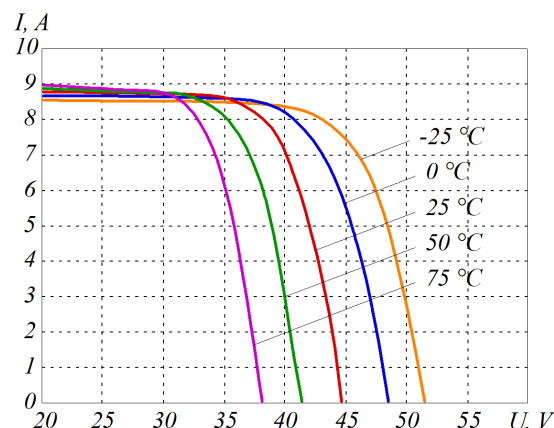
One of the most important characteristics of solar panels is its current-voltage characteristic, the shape of which depends on the level of solar radiation and temperature. For an example, consider the volt-ampere characteristics of the Era-370W-24V-Mono solar panel (figure 1).

At the same time, the current-voltage characteristics of the solar panel largely depend on the temperature of the panel, while an increase in temperature reduces the generated power (figure 2). Based on figure 2, it can be seen that when the solar panels are heated, the voltage and current, and therefore the power generated by the solar power, decreases. So, it makes sense to cool the solar panels. Thus, lowering the temperature of a heated solar panel from 75 °C to -25 °C will increase the maximum generated power by approximately 35%.

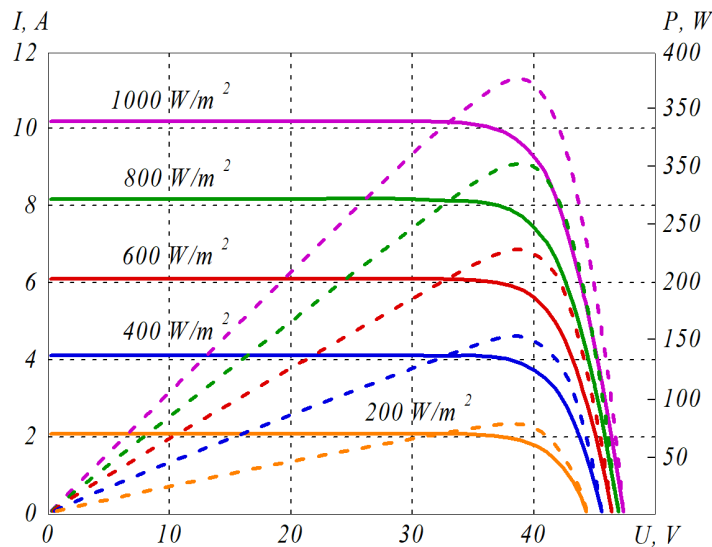
When the current consumed by the solar panel changes, the voltage of the solar panel changes, and thus the power generated by the solar panel changes. At the same time, the dependence of



**Figure 1.** Current-voltage characteristics of solar panel Era-370W-24V-Mono at different levels of solar radiation (with ambient temperature of 25 °C).



**Figure 2.** Current-voltage characteristics of solar panel Era-370W-24V at different temperatures (at a sun radiation intensity of 1000  $W/m^2$ ).

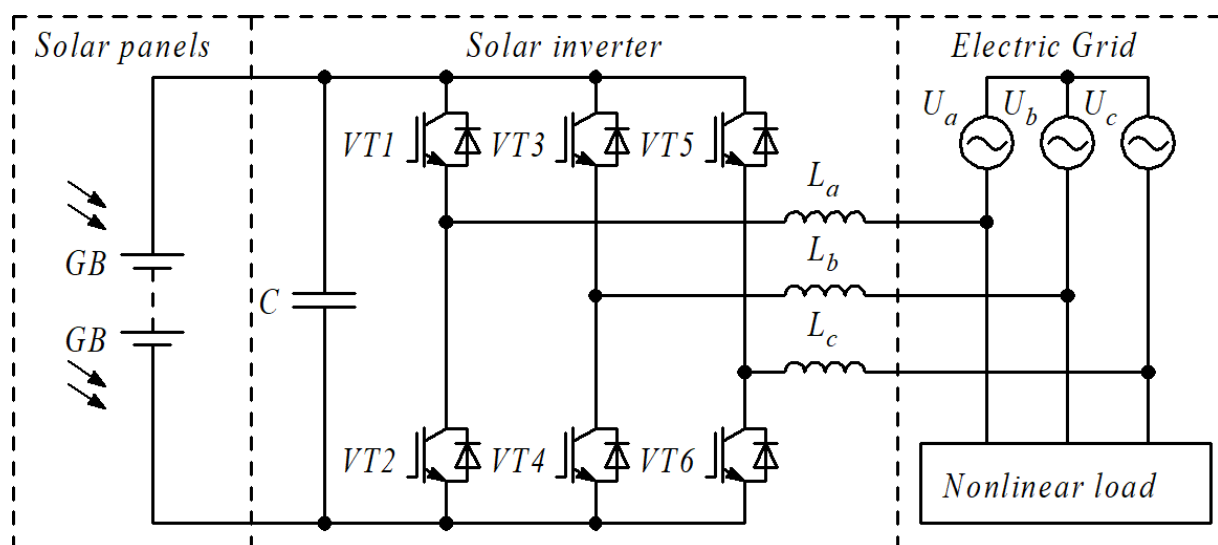


**Figure 3.** Dependence of the maximum power of the solar panel as a function of the consumed current and the level of solar radiation.

the power of the solar panel on the consumed current is shown in (figure 3). It can be seen that the solar panel has a point of generation of maximum power, which is determined by a certain amount of current consumed by the solar panel. Thus, by adjusting the amount of current consumed by the solar panel, it is possible to enter the maximum power generation mode. This algorithm is called MPPT – maximum power point tracking [9, 10]. Most traditional MPPT algorithms are based on the concept of tilt tracking. One of the typical tilt tracking methods is the algorithm Perturb and Observe (P&O). The disadvantage of this method is the loss of generated power during the search for the point of maximum power generation, which can last for a considerable time.

Determining the maximum power generation point can also be done by exact calculation by polynomial approximation of the solar panel current-voltage characteristics and using solar radiation and temperature sensors [11, 12].

Polynomial approximation of the current-voltage characteristics of the Era-370W-24V-Mono



**Figure 4.** Power generation system “solar panels – solar inverter – electric grid”.

sleepers panel at different levels of solar radiation:

- at a solar radiation intensity of 1000 W/m<sup>2</sup>:

$$i_{pv1000}(u) = -44500u^5 + 31375u^4 - 7716u^3 + 764.46u^2 - 24.9u + 18.2; \quad (1)$$

- at a solar radiation intensity of 800 W/m<sup>2</sup>:

$$i_{pv800}(u) = -46402u^5 + 33583u^4 - 8494u^3 + 866.8u^2 - 29.1u + 14.7; \quad (2)$$

- at a solar radiation intensity of 600 W/m<sup>2</sup>:

$$i_{pv600}(u) = -1980888u^6 + 176912u^5 - 60166u^4 + 9587u^3 - 698.9u^2 + 18u + 11; \quad (3)$$

- at a solar radiation intensity of 400 W/m<sup>2</sup>:

$$i_{pv400}(u) = -209032u^6 + 189327u^5 - 64729u^4 + 10272u^3 - 739.4u^2 + 18.68u + 7.097. \quad (4)$$

The obtained polynomials make it possible to analytically determine the generation point of the maximum power of the solar panel as a function of the current consumed by the hybrid inverter. Thus, by regulation of the solar panel current, it is possible to obtain the maximum power that is functionally realized by the semiconductor converter that takes power from the solar panel.

Converters, called solar inverters or hybrid inverters, perform the functions of selecting electrical energy from solar panels, operating in the maximum power generation mode, and ensuring the transmission of electrical energy to the general industrial electrical network (figure 4) [13, 14].

The standards EN 50549-1, EN 50549-2 define the requirements for generating plants to be connected in parallel with distribution networks [15, 16].

A solar inverter, when generating electrical energy to the electrical network, can work both in the voltage-source mode and in the current-source mode. When operating in current-source mode, the solar inverter must operate in a mode similar to the operation of a power active filter with forced formation of a given shape and phase of the current. At the same time, the generation mode in the current source mode has significant advantages, namely: the possibility of operation in the power factor mode close to unity; operation in reactive power compensation mode; operation in the mode of compensation of higher current harmonics caused by non-linear and impulse load of the electrical network. At the same time, the low level of higher harmonics of currents in the electric network causes a decrease in additional power losses in it.

At the same time, for operation in the power active filter mode, a necessary condition for stable operation is the need to maintain the voltage on the solar panels higher than the amplitude value of the line voltage of the electrical network [17, 18].

To maintain this condition, it is necessary to connect a fairly significant number of solar panels to a solar inverter. When the voltage generated by the solar panels is lower than the amplitude value of the line voltage of the network, then it is necessary to use additional step-up DC–DC converters between the solar panels and the solar inverter [19, 20]. Also, DC–DC converters can be used, providing galvanic isolation between the input and output of the converter. These converters: flyback converter; forward converter; half-bridge push-pull converter junction; full bridge DC–DC converter.

In addition to the function of increasing the voltage from solar panels, DC–DC converters also provide the function of extracting electricity from the solar battery to chemical energy storage devices, such as acid, alkaline or lithium-ion batteries, implemented by semiconductor converters. To implement the function of maximum power selection from the solar panel in

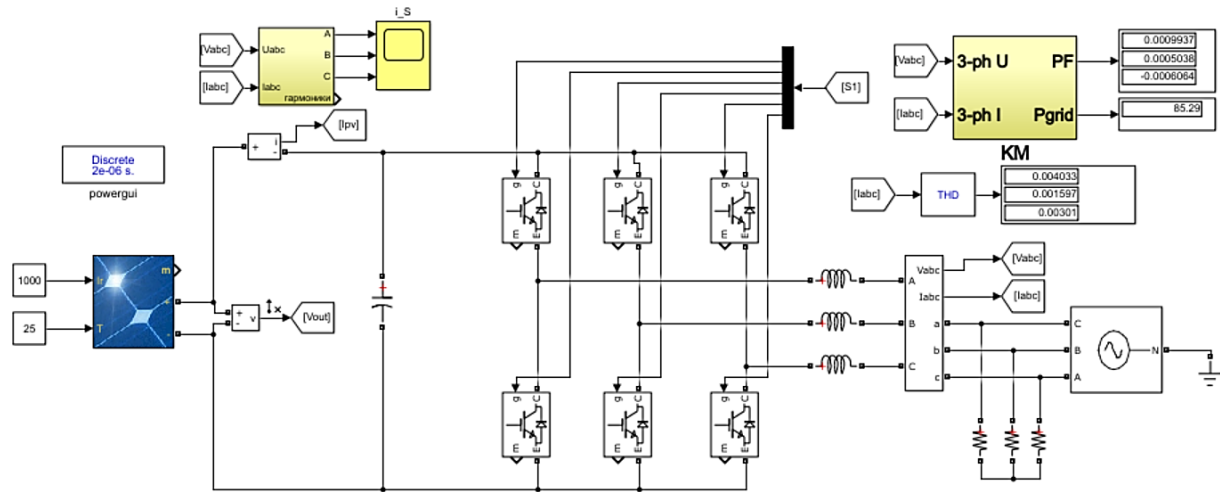


Figure 5. Matlab model of the system “solar panels – solar inverter – electric network”.

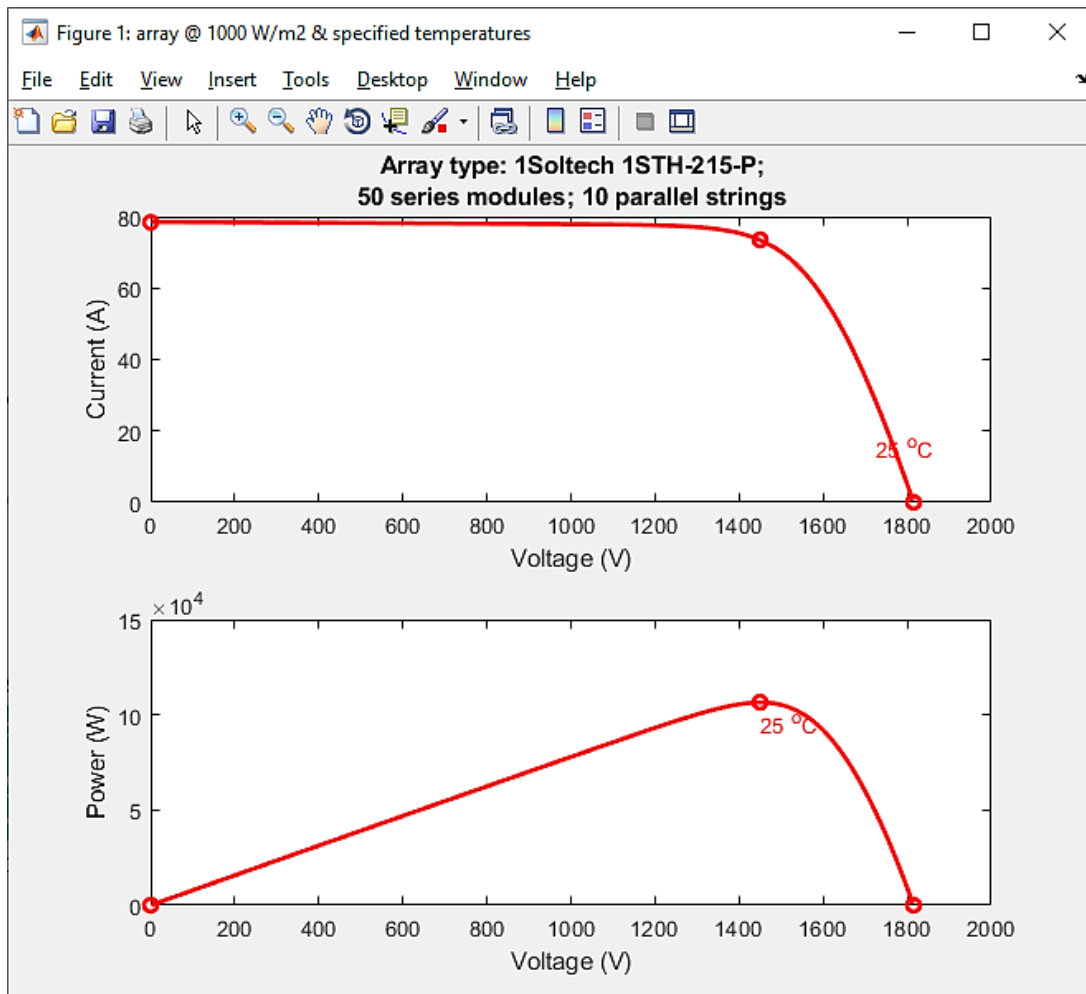


Figure 6. Current-voltage characteristic and power-voltage characteristic.



**Table 1.** Main parameters of Matlab model.

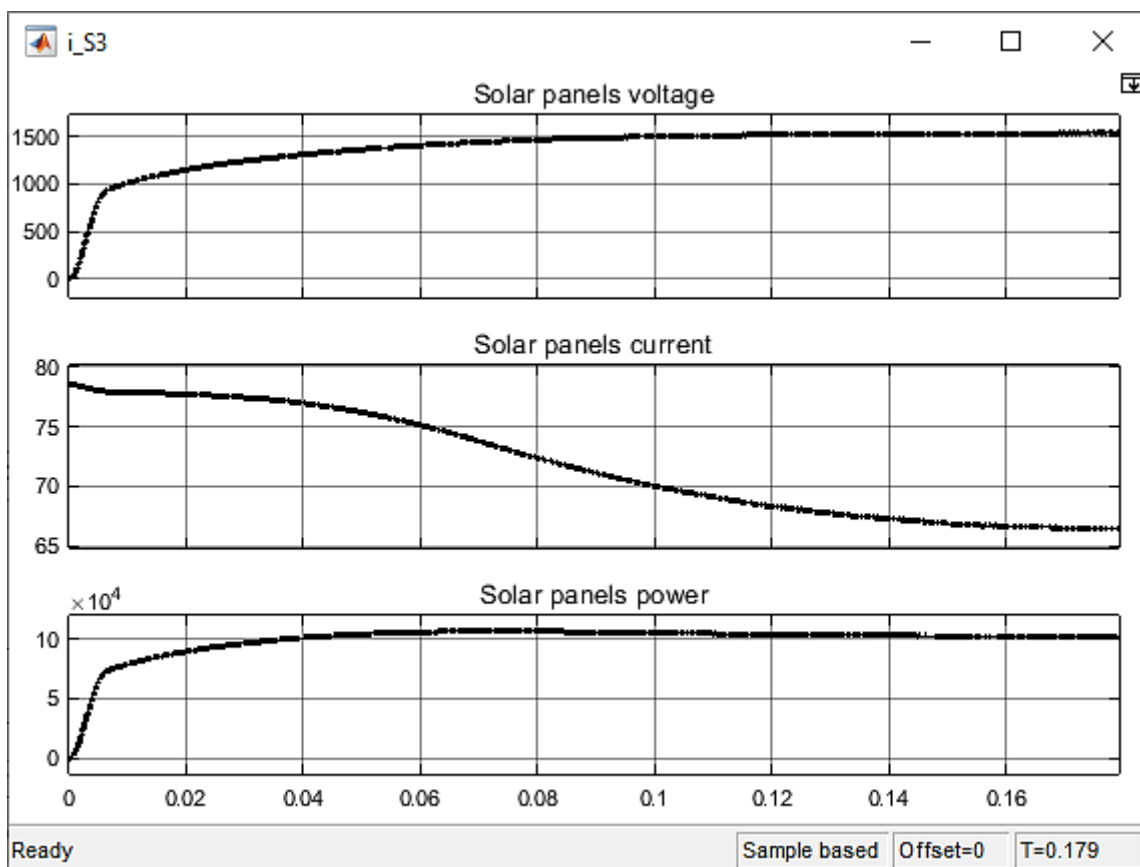
Parameter	Value
Network voltage, V	220/380
Network load active resistance, Ohm	5
Network inductance, mH	0.1
Inductance of the inductor of the hybrid filter, mH	0.6
Hybrid inverter capacitor capacity, mF	2
PWM frequency, kHz	1-10

Current-voltage characteristic of a set of 500 solar panels simulated in Matlab model is shown in figure 6.

The control system of the hybrid inverter is implemented on the basis of the control system of the power active filter with PWM control with an adjustable modulation frequency from 1 kHz to 10 kHz. The structure of the control system implemented in the model is shown in figure 7.

The implementation of the maximum power selection in the hybrid inverter is implemented by controlling the phase current of the solar inverter by setting the modulation coefficient.

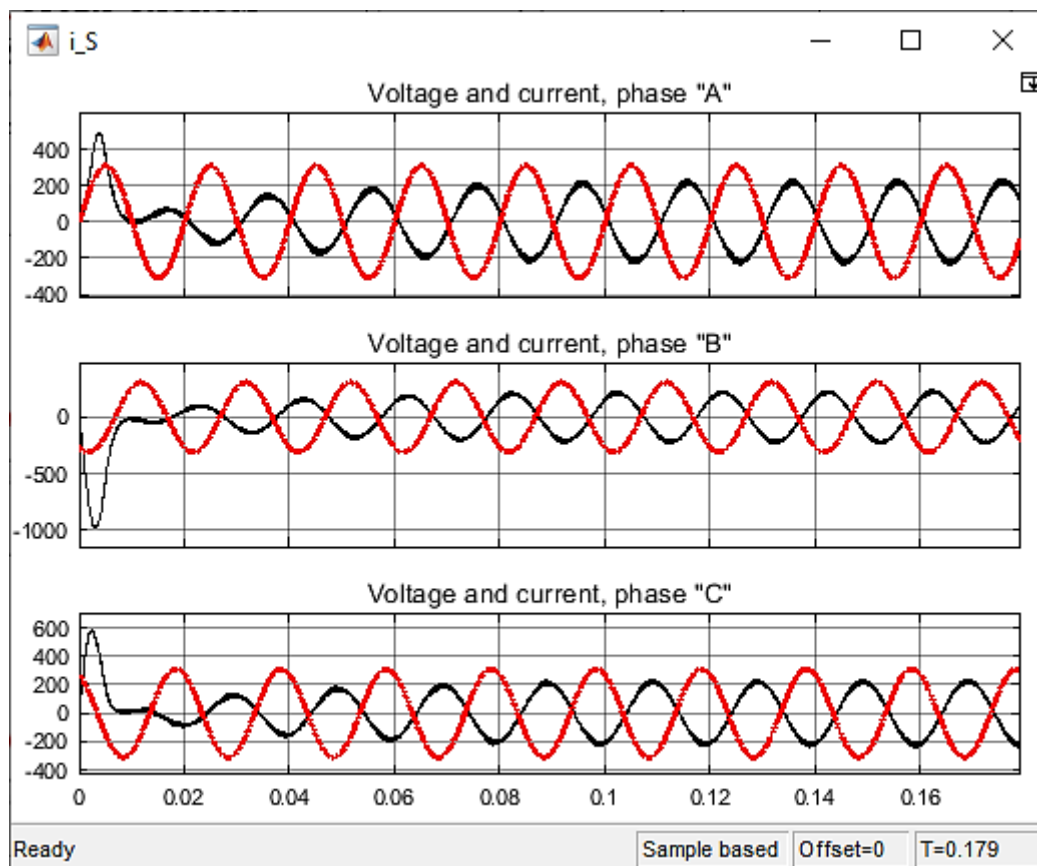
Transient processes of current, voltage and power of solar panels at the start of the solar inverter are shown in figure 8. As can be seen from figure 8, the voltage of the block of solar panels increases from zero during startup.



**Figure 8.** Voltage, current and power of a solar panel delivered by a hybrid inverter.



As is known, the condition for the implementation of the power factor correction mode and the formation of the sinusoidal form of the generated current is that the voltage in the direct current link of the solar inverter is higher than the amplitude value of the line voltage of the network, into which the energy from the solar panels will be transferred. Therefore, to improve the start-up mode of the solar inverter, it is advisable to perform the start-up with a precharged capacitor of the inverter to the level of a larger amplitude value of the line voltage of the network (figure 9).



**Figure 9.** The transition process of transferring electrical energy from the hybrid inverter.

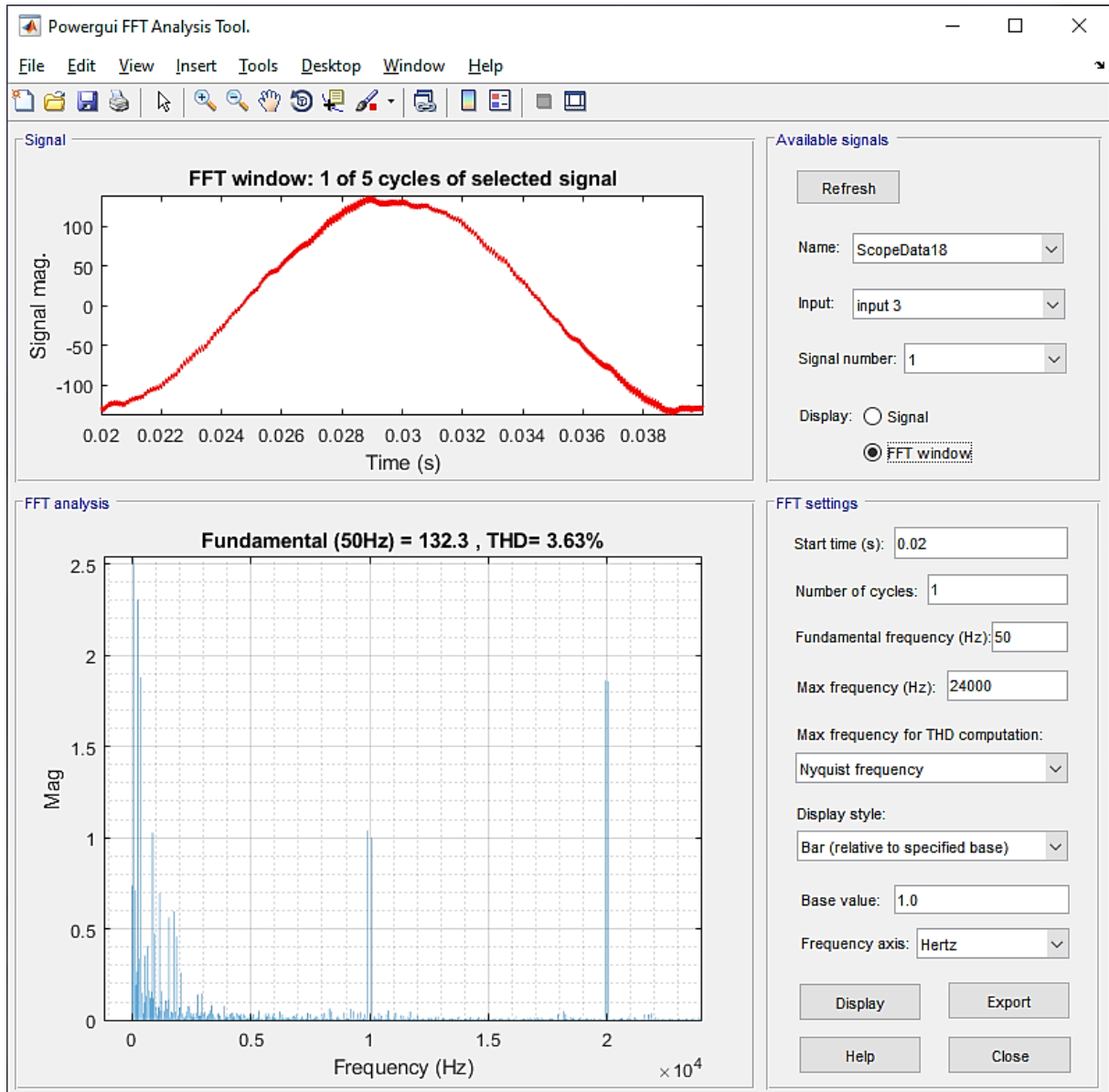
The power factor in the mode of generating electricity to the electric grid is 0.991. The results of the harmonic analysis of the form of the current generated from the solar inverter to the electric grid are shown in figure 10.

As can be seen from figure 10, the current generated from the solar inverter to the electrical network has a harmonic distortion coefficient equal to 3.63%, and the amplitude value of all harmonics in the spectrum does not exceed 2.4%, which meets the requirements of international standards.

To calculate the efficiency of the hybrid inverter, the characteristics of the IGBT module CM1200DC-34S, Mitsubishi with a nominal current of 1200 A and a nominal voltage of 1700 V were taken. The characteristics for which the calculation was given and which determine power losses are shown in figure 11.

The results of polynomial approximation of the energy characteristics of power transistors at a temperature of 25 °C are given in the following expressions.

When using the developed algorithm, power losses were determined, as well as the quality of



**Figure 10.** Harmonic analysis of the shape of the current generated from the solar inverter.

the realized current when setting different modulation frequencies.

$$U_{ce}(I_c) = -0.162I^4 + 0.942I^3 - 2.009I^2 + 2.746I + 0.57; \quad (5)$$

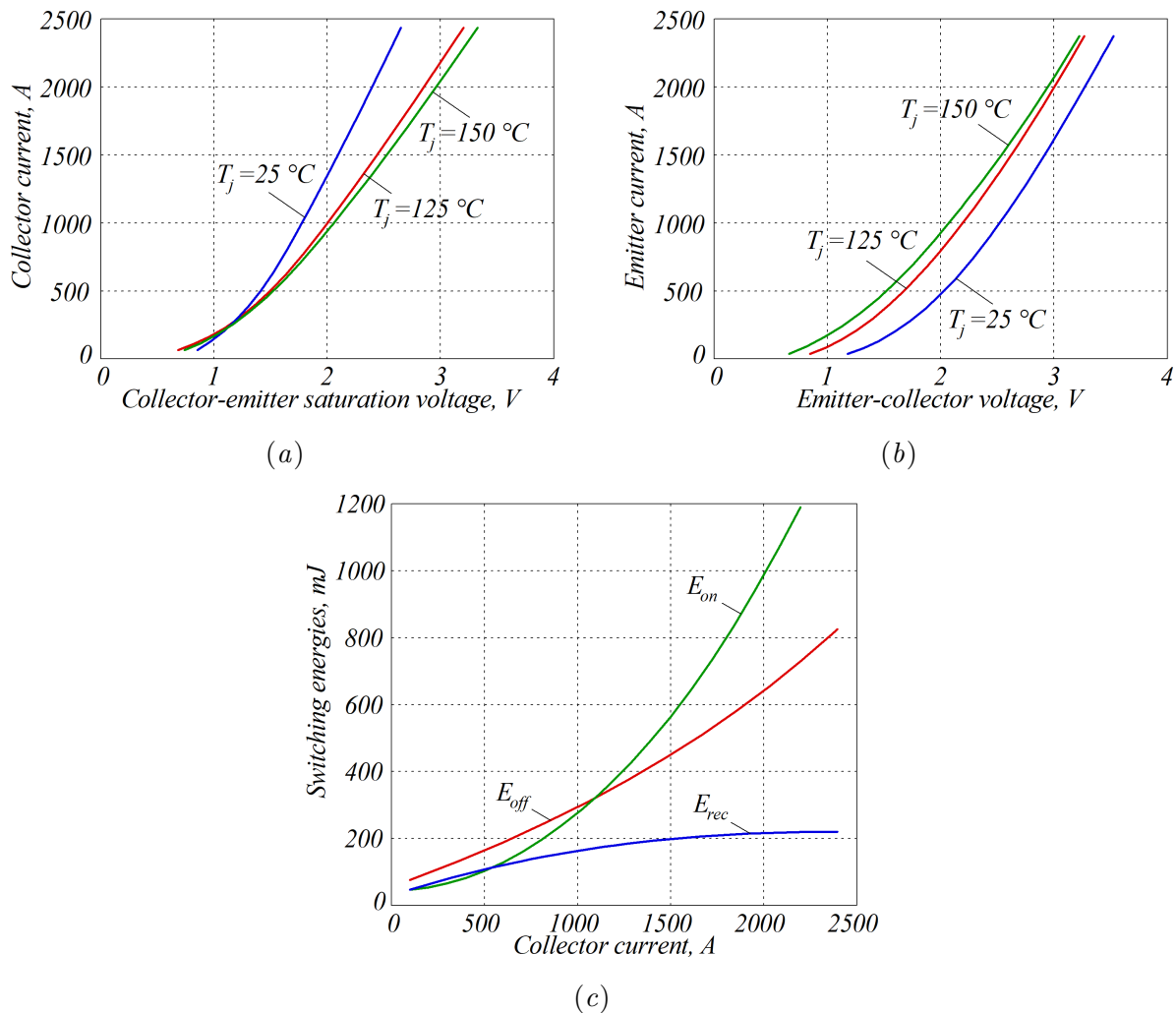
$$U_{fw}(I_f) = -0.185I^4 + 1.054I^3 - 2.171I^2 + 2.735I + 0.68; \quad (6)$$

$$E_{on}(I_c) = 0.2406I^2 - 0.006I + 0.0496; \quad (7)$$

$$E_{off}(I_c) = 0.0587I^2 + 0.1842I + 0.0547; \quad (8)$$

$$E_{rec}(I_f) = 0.0054I^5 - 0.0368I^4 + 0.1002I^3 - 0.1601I^2 + 0.2309I + 0.0227. \quad (9)$$

The calculation carried out during modeling determined the dependence of the amount of power loss in one power switch of the inverter as a function of the PWM frequency in figure 12.



**Figure 11.** Energy characteristics of the CM1200DC-34S module: (a) volt-ampere characteristic of the transistor; (b) volt-ampere characteristic of the reverse diode; (c) dependences of the switch-on energy, switch-off energy and reverse diode recovery energy from the commutated current.

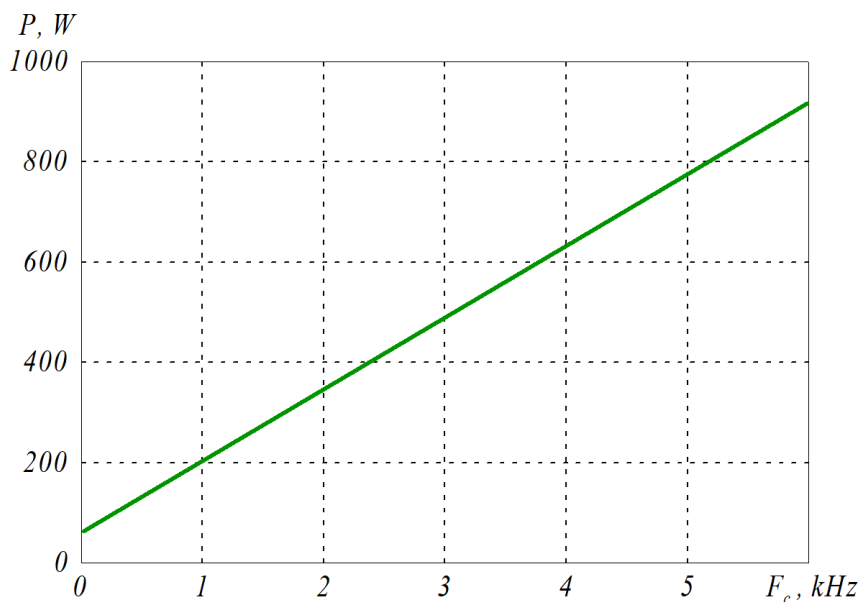
Dependence of power losses in the CM1200DC-34S power transistor on the PWM frequency at a DC link voltage of 1500 V and a current amplitude of 223 A (maximum power point of solar panels).

Thus, the efficiency of the hybrid inverter when transferring electricity from the solar panels to the electrical network was from 98.4% at a PWM frequency of 1 kHz to 92.7% at a PWM frequency of 6 kHz.

### 3. Conclusions

The article shows that the generated power from solar panels has a maximum point, which depends on the amount of current consumed from the solar panel. The circuit solutions of semiconductor converters are determined, which provide the maximum power extraction modes from solar panels and the transmission of electricity to general industrial electrical networks with high quality parameters.

The developed computer simulation model of a system for generating electricity from solar



**Figure 12.** Dependence of power losses in the CM1200DC-34S power transistor.

panels of Soltech 1STH-215P types to a general industrial network using a solar inverter with a PWM control system, which makes it possible to transfer electrical energy with a power factor close to unity (0.98) with a low level of higher harmonics (total harmonic distortion 3.36%).

The model also explores the transients in the electrical network and the solar panel when starting the converter. Recommendations are given for starting a solar inverter with a pre-charged capacitor, which will improve the quality of the current in the start mode.

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