V International Scientific and Technical Conference Actual Issues of Power Supply Systems

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AIPCP25-CF-ICAIPSS2025-00121 | Article

Improving The Energy Efficiency of Solar PV Systems by Optimizing the Operation of Inverters

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Abstract. The paper analyzes the current state and trends in the development of solar energy as one of the key areas of renewable energy. The physical foundations of photoelectric conversion of solar radiation into electrical energy based on semiconductor structures with a p–n junction are considered. The main types of photovoltaic systems and their structural elements are given: solar panels, batteries, charge controllers, inverters and voltage stabilizers. Particular attention is paid to the principles of operation of inverters of various types (autonomous, on-grid and hybrid), their energy efficiency and impact on the overall efficiency of the system. It is shown that the use of silicon-based photovoltaic converters provides a high level of reliability and durability of the installation with minimal operating costs. The technical and environmental feasibility of introducing solar energy systems in autonomous and hybrid energy complexes is substantiated.

INTRODUCTION

The rapid growth of energy consumption is one of the most characteristic features of the technical activity of mankind in the second half of the 20th century. Until recently, the development of the energy sector did not encounter fundamental difficulties. The increase in energy production was mainly due to an increase in the production of oil and gas, which are the most convenient to consume. However, the energy sector turned out to be the first major sector of the world economy that faced a situation of depletion of its traditional raw material base. In the early 70s, the energy crisis broke out in many countries. One of the reasons for this crisis was the limitation of fossil energy resources. In addition, oil, gas and coal are also the most valuable raw materials for the intensively developing chemical industry. Therefore, it is now increasingly difficult to maintain a high rate of energy development by using only traditional fossil energy sources [1].

Nuclear power has also recently faced significant difficulties, primarily related to the need to sharply increase the cost of ensuring the safety of nuclear power plants.

Pollution of the environment by the products of combustion of fossil sources, primarily coal and nuclear fuel, is the cause of the deterioration of the environmental situation on Earth. The "thermal pollution" of the planet, which occurs during the combustion of any type of fuel, is also significant. The permissible upper limit of energy production on Earth, according to the estimates of a number of scientists, is only two orders of magnitude higher than the current world average on the Earth's surface by about one degree. Disruption of the planet's energy balance on such a scale can lead to irreversible dangerous climate change. These circumstances determine the growing role of renewable energy sources, the widespread use of which will not lead to a violation of the Earth's ecological balance [2].

Most renewable energies – hydropower, ocean mechanical and thermal energy, wind and geothermal energy – have either limited potential or significant difficulties in widespread use. The total potential of most renewable energy sources will increase energy consumption from the current level by only an order of magnitude. But there is another source of energy – the Sun. Our luminary supplies the Earth with a power of about 1017 watts - this is the power of the sun, the diameter of which is 12.7 thousand km. The intensity of sunlight at sea level in southern latitudes, when the Sun is at its zenith, is 1 kW/m^2. With the development of highly efficient methods for converting solar energy, the Sun can provide exponentially increasing energy needs for many hundreds of years [3].

To assess the efficiency of photovoltaic converters that directly convert solar energy into electrical energy with the help of semiconductor photovoltaic cells, we will introduce the concept of the efficiency of a photocell, defined as the ratio of the power of electricity generated by this cell to the power of a solar bunny falling on the surface of the photocell. In order to produce 1012 W of electricity, it would be necessary to cover an area of 4 · 1010 m^2, equal to a square with a side of 200 km, with photoconverters. That is, the "low density" of solar radiation is not an obstacle to the development of solar radiation. large-scale solar energy [4].

The above considerations are a strong enough argument: the problem of converting solar energy must be solved today in order to use this energy tomorrow. We can at least jokingly consider this problem within the framework of solving energy problems of controlled thermonuclear fusion, when an efficient reactor (the Sun) was created by nature itself and provides a resource of reliable and safe operation for many millions of years, and our task is only to develop a ground-based converter station. Recently, extensive research has been carried out in the world in the field of solar energy, which has shown that in the near future this method of energy production can become economically justified and find wide application.

The main areas of work in the field of solar energy conversion at present are:

– direct thermal heating (production of thermal energy) and thermodynamic transformation (production of electrical energy with intermediate conversion of solar energy into thermal energy);
– photovoltaic conversion of solar energy.

Direct thermal heating is the simplest method of converting solar energy and is widely used in Uzbekistan and in the countries of the equatorial belt in solar heating, hot water supply, cooling buildings, desalination, etc. Water or other liquid, being in contact with the absorber, is heated and diverted from it with the help of a pump or natural circulation. The heated liquid then enters the storage facility, from where it is consumed as needed. Such a device resembles domestic hot water supply systems [5].

Electricity is the most convenient type of energy for use and transmission. Therefore, the interest of researchers in the development and creation of solar power plants using the intermediate conversion of solar energy into heat with its subsequent conversion into electricity is understandable.

There are two types of solar thermal power plants in the world today: 1) tower-type (Figure 1) with the concentration of solar energy on one solar receiver, carried out with the help of a large number of flat mirrors; 2) dispersed systems of paraboloids and parabolic cylinders, in the focus of which heat receivers and low-power converters are placed [6-7].

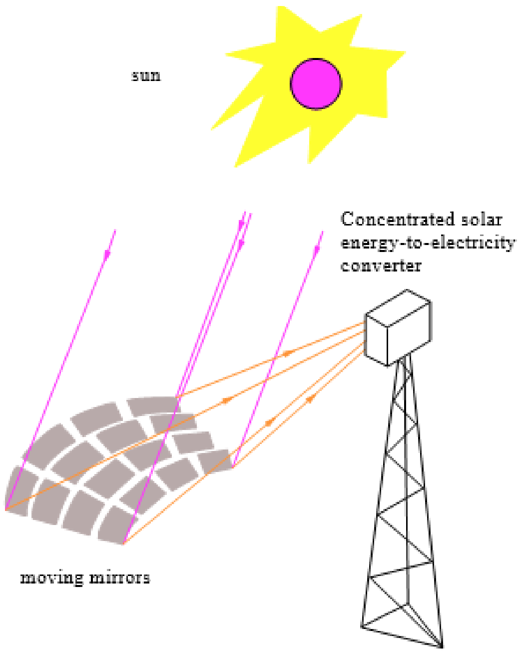

FIGURE 1. Solar power plant of the "tower" type.

EXPERIMENTAL RESEARCH

Photovoltaic cells are based on a semiconductor structure with *a p–n* junction (Figure 2) that occurs at the boundary of two semiconductors with different conduction mechanisms. Note that this terminology originates from the English words *positive* and *negative*. Various types of conductivity are obtained by changing the type of impurities introduced into the semiconductor. Mendeleev, introduced into the crystal lattice of silicon, give the latter hole (positive) conductivity, and impurities of group V - electronic (negative) [8]. The contact of *p*- or n-semiconductors leads to the formation of a contact electric field between them, which plays an extremely important role in the operation of a solar photocell. Let us explain the reason for the occurrence of the contact potential difference. When *p*- and *n-type* semiconductors are combined in one single crystal there is a diffusion flow of electrons from the n-type semiconductor to the semiconductor *p. As a result of this process*, the portion of the *p-type* semiconductor adjacent to the p–n *junction will be negatively charged, while the* portion of the *n-type* semiconductor adjacent to the p–n *junction* will acquire a positive charge. Thus, near *p–n* A double charged layer is formed, which counteracts the process of diffusion of electrons and holes. Indeed, diffusion tends to create a flow of electrons from the *n-region to the p-region, while the field of the charged layer, on the contrary, tends to return electrons to the* n-region. Similarly, the field in the *p–n* junction counteracts the diffusion of holes from *p*- to *n*-region. As a result of two processes acting in opposite directions (diffusion and motion of current carriers in an electric field), a stationary, equilibrium state is established: a charged layer appears at the boundary, preventing the penetration of electrons from the n-semiconductor, and holes from *the p-semiconductor. In other words, an* energy (potential) barrier arises in the p–*n* junction region, to overcome which electrons *from an* n-semiconductor and holes from *a* p-semiconductor must expend certain energy. Without dwelling on the description of the electrical characteristics *of the p–n* junction, which is widely used in rectifiers, transistors, and other semiconductor devices, let us consider the operation of *the p-n* junction in photovoltaic cells [9].

In a homogeneous semiconductor, photoexcitation increases only the energy of electrons and holes without separating them in space; that is, the electrons and holes become separated in “energy space” but remain close together in geometric space within the p–n junction region (Figure 2).

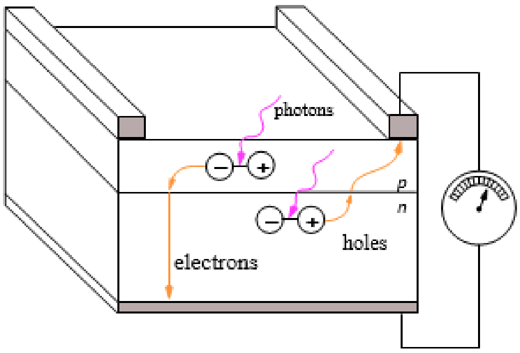

FIGURE 2. Energy-space separation of photoexcited electrons and holes.

"Non-basic" carriers *generated near* the p–n junction (holes in *the n-semiconductor and electrons in the p-semiconductor) diffuse to* the *p–n* junction, are picked up by the *p–n* junction field, and ejected into the semiconductor, where they become the main carriers: the electrons will be localized in the *n-type semiconductor*, and the holes will be localized in the p-type semiconductor-Sort of. As a result*, the p-type semiconductor receives an excess positive charge, and the* n-type semiconductor *receives a negative charge. A* potential difference occurs between the n- *and p-regions of the photocell – photoEMF. The polarity of the photoEMF corresponds to the "forward" shift of the* p–n *junction, which lowers the height of the barrier and promotes the injection of holes from the p-region into n.* As a result of the action of these two opposite mechanisms – the accumulation of current carriers under the influence of light and their outflow due to a decrease in the height of the potential barrier – different values of photoEMF are established at different light intensities. At the same time, the value of photoEMF in a wide range of illuminations increases in proportion to the logarithm of light intensity. when the potential barrier turns out to be practically zero, the value of the photoEMF reaches "saturation" and becomes equal to the height of the barrier at the unilluminated *p–n* junction. When illuminated by direct sunlight, as well as by solar radiation concentrated up to 100 – 1000 times, the value of the photoEMF is 50 – 85% of the value of the contact difference in the potential of the *p–n* transition [10-13].

A solar photocell is made on the basis of a wafer made of a semiconductor material, such as silicon. Regions with *p*- and *n*-types of conductivity are created in the wafer (Figure 2). For example, the method of diffusion of impurities or the method of building one semiconductor onto another is used as methods for creating these regions. and the upper one is made in the form of a comb structure (thin strips connected by a relatively wide current-collecting busbar).

The main material for the production of solar cells is silicon. The technology for producing semiconductor silicon and photovoltaic cells based on it is based on methods developed in microelectronics, the most advanced industrial technology. Silicon, apparently, is generally one of the most studied materials in nature, and also the second most abundant after oxygen. Photocells made of single-crystal silicon combine the advantages of using a relatively cheap semiconductor material with the high parameters of devices obtained on its basis [14-15].

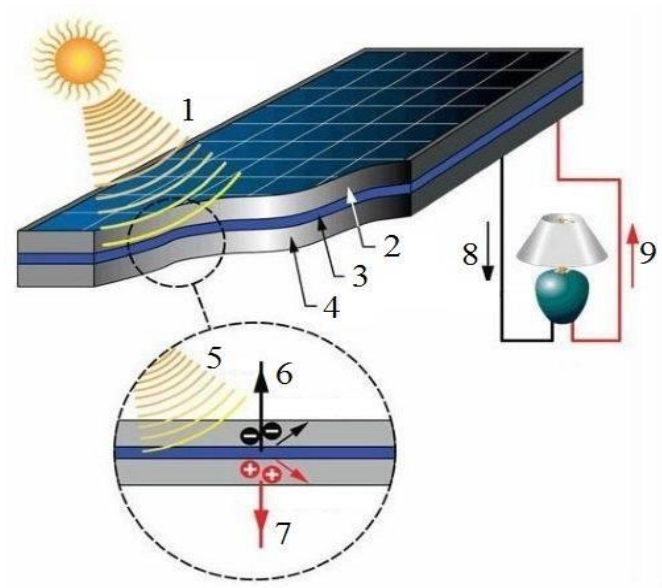

FIGURE 3. Solar battery device: 1 – sunlight; 2 – n-layer; 3 – transition; 4 – p-layer; 5 – photons; 6 – electron flow; 7 – flow of "holes"; 8 – electric current; 9 – load.

A solar battery is a system of interconnected elements that serve to convert incoming sunlight into electric current.

This system consists of the following components:

- A solar panel is two tightly packed layers of materials with different conductivity. According to the manufacturing technology, panels can be polycrystalline or monocrystalline.
- Battery (stores and stores energy).
- Charge controller.
- Inverter is a converter of direct electric current received from a solar battery into alternating current.
- Voltage stabilizer. It is used to obtain the desired voltage.

Photons (particles of light) hitting the surface of the semiconductor transfer their energy to the electrons of the semiconductor. After that, the electrons that have been knocked out of the semiconductor overcome the transition using additional energy. Thus, positive electrons leave *the n-conductor, passing into* the p-conductor, negative electrons – vice versa (Figure 3).

RESEARCH RESULTS

In order for the electric current *I* to appear in the circuit, the sunlit battery is short-circuited to a load with resistance R_h. The amount of current is determined by the load resistance, the intensity of illumination and the quality of the photovoltaic converter. The power P_h released at the load is determined by the product $\boldsymbol{P_h = I_n U_n}$, where U_n *is the* voltage at the battery terminals [16-18].

Some individual solar cells are connected in series and parallel to increase the output parameters (power, voltage and current). When the elements are connected in parallel, the output current increases, and when the elements are connected in series, the output voltage increases. By combining these two connection methods, it is possible to increase the current and voltage. If, with such a connection, one of the solar cells fails, this does not lead to the failure of the entire system, that is, the reliability of the entire battery increases.

When the battery is heated by the sun, the electromotive force decreases. One of the most important technical parameters of a solar cell is its net power. It is determined by the output current and voltage. These two parameters depend on the intensity of sunlight supplied to the battery [19].

Solar cell batteries contain diodes. Traditionally, there are four of them on the battery - one for every fourth part. Diodes protect the parts of the battery from failure that have darkened for any reason. At the same time, the battery temporarily generates an output power that is 25% less than with normal illumination of the entire battery surface. In the absence of diodes, solar cells will overheat and fail, because they themselves consume current during the darkening (discharge the batteries), and when using diodes, the current does not flow through them.

The resulting electrical energy accumulated in the batteries is converted into a load. Accumulators are chemical sources of current. Their charging occurs only when a potential greater than the voltage of the accumulator is applied to them. The number of solar cells connected in series and in parallel should be equal to such that the load current of the battery supplies the required amount of charging current, and the operating voltage supplied to the accumulators, taking into account the voltage drop in the charging circuit, is slightly higher than the voltage of the accumulators. The recharging process is controlled by a special controller. In the case of cyclic charging, a direct current or a constant charge voltage is required. The battery, in good light, is quickly charged to 90% of its nominal capacity, and then, much slower, to full capacity [20].

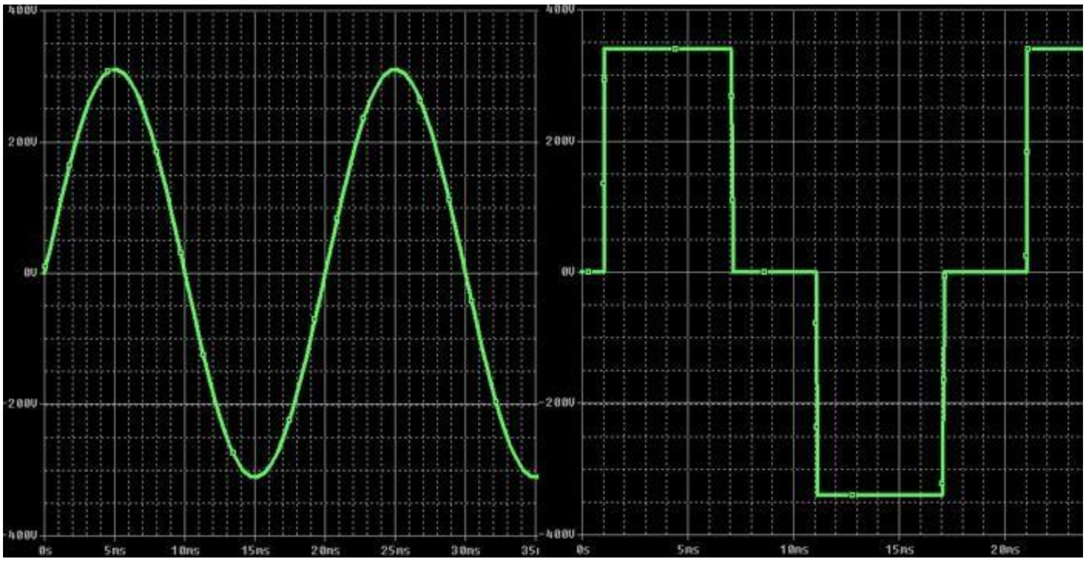

FIGURE 4. Inverter waveform – Sine wave (left), modified sine wave (right)

An inverter is a device that converts direct current received from solar panels into alternating current under the required voltage, this is its main task.

Alternating current is used to power household appliances.

A solar battery that does not use an inverter can power DC power receivers, including energy-saving light sources and various portable equipment, but the centralized electrical grid and most electrical appliances use alternating current. Thanks to this, an inverter is almost indispensable for solar panels [21].

Depending on the output signal, the following types of inverters are distinguished:

- Inverters with pure sine wave output;
- Inverters generating modified sinusoidal (quasi-sinusoidal) output signal or meander;

Inverters, with a sine wave output, can power a variety of AC loads. Inverters with a quasi-sinusoidal output signal that has a square voltage shape (meander) are not suitable for many loads, such as induction motors.

Inverters with quasi-sinusoidal output voltage are significantly cheaper than sine wave inverters. The high price of sinusoidal inverters is fully compensated by the quality of the energy obtained (Figure 4).

The performance of the inverter depending on the load of solar panels is shown in Figure 5.

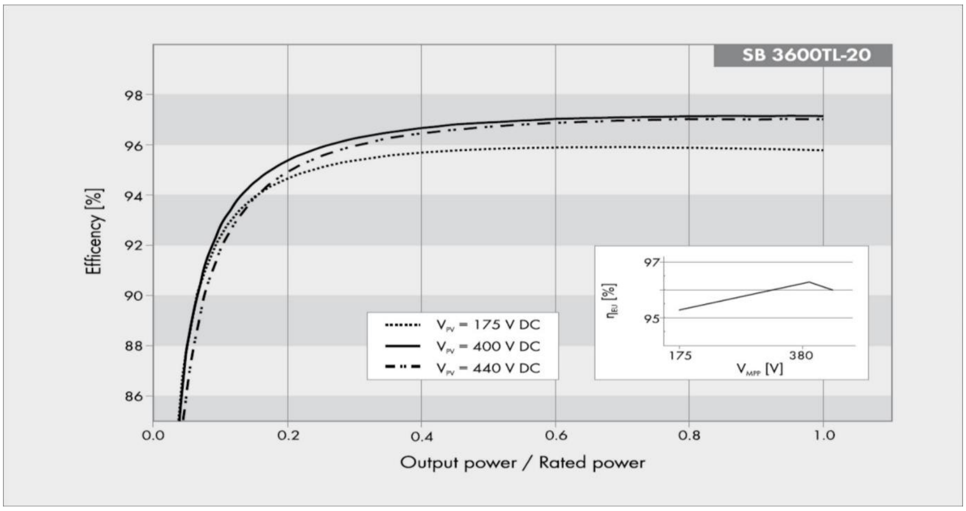

FIGURE 5. Inverter Performance Based on Solar Cell Load

Depending on the type of use, three main types of inverters can be distinguished:

- Off-grid inverters are designed for autonomous photovoltaic systems, they are not connected to the external electrical grid.
- Grid inverters are inverters that operate synchronously with the traditional power grid. In addition to their main functions, these devices include adjusting the operating parameters of the network: amplitude, voltage frequency, and so on. In the event of a power failure, the inverter will automatically turn off. This kind of inverter is suitable for solar systems that work without batteries [22].
- Hybrid – also known as a "battery-mains" converter, which combines the properties of autonomous and network devices. This type of inverter has many settings for the optimal operation of the solar system in the presence of batteries and from the general electrical one.

The standalone converter has a power range from 100 to 8000 watts. To determine the size of a suitable inverter, which is needed in a particular case, you need to calculate the total load of devices in the power supply network. This is done in this way: check the maximum power of each device per unit of operating time and put them together.

Synchronous inverters allow you to store the received energy in the grid. If this type of inverter is installed for solar panels, then the excess unused energy is redirected to the main power grid. If devices are used, the total power of which exceeds the capabilities of the solar installation, then the device will take the missing electricity from the main power grid. Using synchronous inverters in the house, there will never be a sudden power outage, because there will always be a charged battery. And on days when the efficiency of solar panels is quite low, the devices will work from the usual power grid [23].

Hybrid inverters are more expensive equipment that has the advantages of the first two types of converters. Choosing hybrid inverters is the best for creating a solar grid in your home, but due to the price point, not everyone will be able to afford them. Therefore, you should always choose the device that will be preferable to the owner of the house in terms of his capabilities and the parameters of the electrical network of the house. The power of the selected converter depends on the maximum power of the load on the AC side and the rated power of the solar panels. The inverter connection diagram is shown in Figure 6.

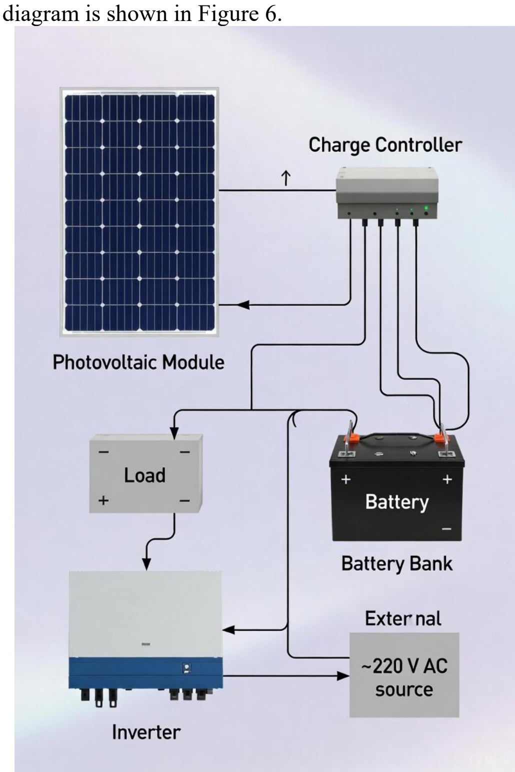

FIGURE 6. Inverter wiring diagram

When a small photovoltaic installation (up to 5 kW) is used, you can get by with one inverter of the appropriate capacity. In the case of a PV system with a capacity of more than 5 kW, it is necessary to provide the system with several inverters operating in a cascade. This will reduce the risk of downtime of solar panels when one converter fails, it is also possible to compare the efficiency of each individual device, as well as analyze the operation of each of them [24].

One of the key criteria for evaluating an inverter is its standard efficiency or efficiency. Expensive inverters have an efficiency of up to 98%. When selecting components for a solar system, inverters with a nominal efficiency of less than 92% should be avoided.

The following advantages of using solar panels to generate electric current can be distinguished:

- ecological compatibility;
- ease of maintenance;
- autonomy of operation;
- noiselessness of operation (achieved by the absence of moving parts);
- long service life;

CONCLUSIONS

In the course of the analysis, the basic principles of the functioning of inverter technologies used in solar power plants are considered, and the key factors affecting the overall efficiency of photovoltaic systems are identified. It is established that the efficiency of energy conversion directly depends on circuit solutions, control algorithms and the quality of matching the inverter with the load and solar modules [25-26].

The use of modern inverters with pulse width modulation, synchronous maximum power point tracking (MPPT) and multi-level structures can significantly reduce losses when converting direct current into alternating current. The additional use of active cooling circuitry, digital control and intelligent phase balancing algorithms improves the overall reliability and energy efficiency of the system.

Thus, the improvement of inverter devices and the introduction of adaptive control methods are key areas for increasing the efficiency of solar power plants. In the future, the development of this area will be determined by the integration of power electronics, energy storage systems and intelligent grid technologies, which will ensure the sustainable and efficient operation of photovoltaic complexes in new generation power systems [25].

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