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ANALYSIS OF TOPOLOGY OF THE AUTOTRANSFORMER FORWARD-FLYBACK CONVERTER FOR PHOTOVOLTAIC PANEL

The analysis of converters controlling only a part of the output power in photovoltaic systems was carried out. The architecture of distributed tracking of the maximum power is considered, which is one of the most promising solutions for overcoming the shortcomings associated with a decrease in the energy efficiency of photovoltaic panels. The topology of the autotransformer forward-flyback converter for photovoltaic panel is given. The principle of operation of the converter and the flow of current in the circuit during switching are presented. The method of calculating the output power of the converter in the DMPPT architecture with a series connection, in which the circuit voltage is fixed by the central inverter, depends on the generated power of the photovoltaic panels connected to one circuit, is obtained. The power generated by photovoltaic panels was calculated depending on the state of their shading.

Keywords: *autotransformer, efficiency, forward-flyback converter, photovoltaic panel, power losses, solar power plant.*

Introduction

The efficiency of solar energy production remains low due to the limitation of the efficiency of solar cells, which are the basis of photovoltaic (PV) systems of electricity production [1, 2].

One of the most important goals of PV power plants is to obtain the maximum possible energy. Due to phenomena related to solar power plant systems, phenomena of decreasing energy efficiency of PV panels usually occur. The most common reasons for reducing energy efficiency are shadows, dirt, temperature changes, etc. [3, 4]. Thus, due to this problem, the power produced by the PV plant can be significantly reduced.

The architecture of distributed maximum power point tracking (DMPPT) is one of the most promising solutions to overcome the shortcomings associated with the reduction of energy efficiency of photovoltaic panels [5, 6]. This architecture has a DC-DC converter designed to track the maximum power point of each PV panel. To provide the greatest flexibility, the converter must be able to step up and down the voltage.

Another desirable characteristic of the converters used in the DMPPT architecture is high efficiency, but one of the main disadvantages is the high cost due to the large number of used converters [7, 8].

Analysis of Recent Research and Publications

In scientific studies, some authors have obtained high efficiency of converters that control only part of the output power, for example, converters with a series connection, converters with parallel power processing, or converters with direct energy transfer [9, 10]. However, for use in PV systems, such topologies of converters are inefficient.

The papers [11, 12] give general approaches that are used for various purposes, for example, to reduce the load, distribute power in proportion to the generator ratings, and increase the service life of batteries. However, for modular sub-panel PV converters, the DC bus voltage is not regulated according to the load change.

There are also some studies devoted to topologies capable of both increasing and decreasing the output power in PV panels [13, 14]. These topologies have the effect of increasing efficiency. But because the intensity of sunlight hitting the panel varies with season, time and weather, the efficiency gains of the system itself are limited.

Thus, the issue of the further search for highly efficient and inexpensive converters of electrical energy is an actual unsolved task.

Purpose and Objectives of the Study

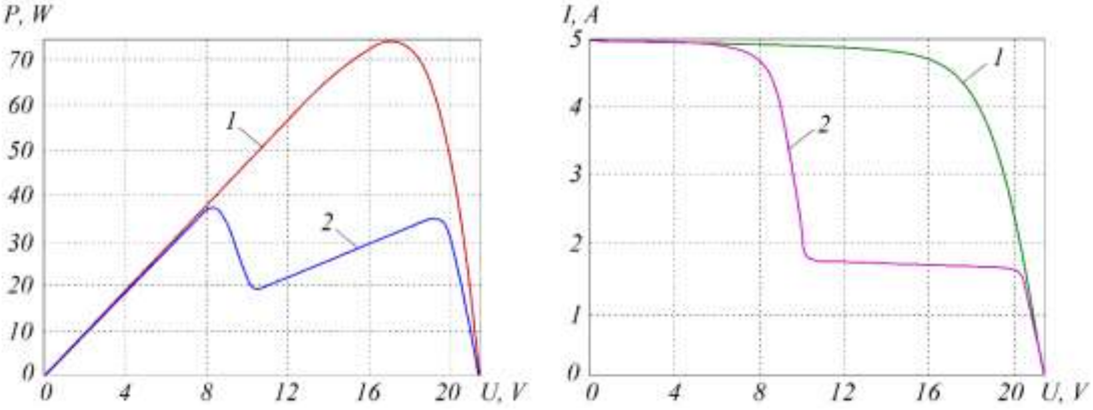
The purpose of the study is to analyze the system of energy conversion at solar power plants through the use of distributed tracking of the maximum power of the photovoltaic panel, which will make it possible to increase the energy efficiency of the converter. To achieve this purpose, the following tasks are set:

- consider the architecture of distributed tracking of the maximum power of the photovoltaic panel;
- present the topology of the autotransformer forward-flyback converter;
- give the results of calculating the power generated by photovoltaic panels.

Main Material of the Study

In the architecture of photovoltaic installations of distributed tracking of maximum power, PV panels are isolated from each other, reducing the impact of negative phenomena on electricity generation [15, 16].

One of the influences on electricity production is the shadow on the PV panel [17, 18]. In Fig. 1 show a comparison of the characteristics of an unshaded and 3/4 shaded PV panel.



a *b*

Figure 1 – *Features of the photovoltaic panel:*
a – power produced by the photovoltaic panel; b – current-voltage characteristics of photovoltaic elements; 1 – unshaded; 2 – 3/4 shaded

As can be seen, there is only one maximum power point for the unshaded PV panel, while the 3/4 shaded PV panel has two maximum power points. In this case, in addition to reducing the power, the influence of the shadow also changes the absolute voltage. Because of this behavior, if the DC-DC converter is only able to step up or step down the output voltage, some PV panels may not operate at their maximum power point, even in DMPPT architectures.

Since the lowest efficiency is achieved when the PV panels are shaded, more PV panels per circuit are required if the DC converter is only capable of stepping down the voltage. On the contrary, when using a step-up converter, fewer photovoltaic panels per circle and more circles are needed [19, 20].

So, to get more flexibility regarding the number of PV panels in circuit, a voltage converter is needed that can both step up and step down the output voltage.

In Fig. 2 shows the topology of the autotransformer forward-flyback converter for PV panel.

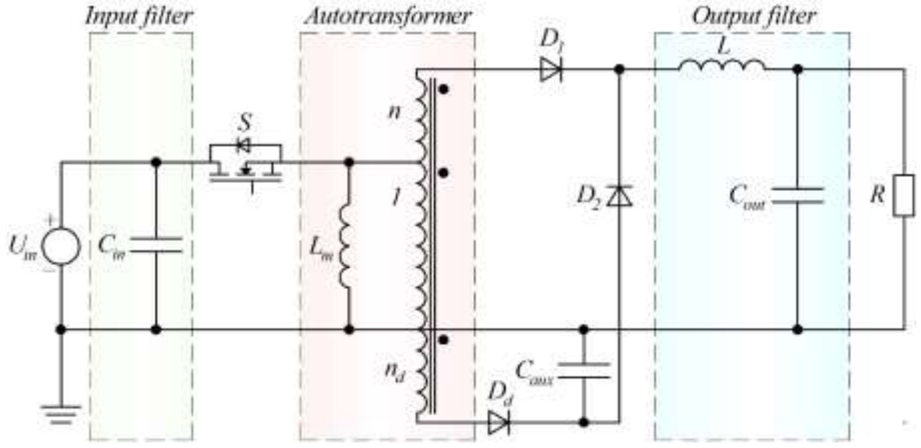


Figure 2 – *Electrical diagram of the autotransformer forward-flyback converter*

The main component of the topology of the autotransformer forward-flyback converter. The method of connecting the autotransformer has two important consequences. On the one hand, due to the fact that the magnetizing inductance of the autotransformer L_m demagnetizes the output filter, its size can be reduced. On the other hand, there is a path when switch *S* is turned on with direct energy transfer from the input source to the output filter without magnetic treatment by the autotransformer. Thus, the efficiency of the converter increases, since only part of the energy is processed magnetically. This principle is similar to converters of serial connection.

During switching on, part of the current transmitted to the load comes directly from the input source U_{in} (direct energy transfer), and the other part is magnetically processed by the autotransformer. While the switch S is on, the inductor of the output filter L and the magnetizing inductance of the autotransformer L_m accumulate energy.

During turn-off, the inductor of the output filter L gives the stored energy to the load through the diode D_2. On the other hand, the magnetizing inductance of the autotransformer L_m gives the accumulated energy to the auxiliary capacitor C_{aux} and the output filter through the demagnetization winding, the demagnetization diode D_d and the diode D_2.

Input voltage, output voltage and voltage on the auxiliary capacitor C_{aux} are represented by U_{in}, U_{out} and U_{Caux}, respectively. The variables I_L and I_{Lm} denote the current through the output inductance L and the magnetizing inductance L_m. The coefficient of turns of the autotransformer of the secondary-primary side is denoted by n and of the demagnetizing winding is denoted by n_d. The conductivity mode is determined by the filter current of the inductor I_L. The value of the duty cycle is represented by T. In order to calculate the transfer function, the input-output voltage balance is performed per second.

$$\left[(1+n)\cdot U_{in} - U_{out}\right]\cdot T = \left(U_{out} - U_{Caux}\right)\cdot(1-T); \tag{1}$$

$$U_{Caux} = \frac{n_d \cdot T}{1-T}\cdot U_{in}; \tag{2}$$

$$\frac{U_{out}}{U_{in}} = \left(1+n+n_d\right)\cdot T. \tag{3}$$

As can be seen, the transfer function of the output voltage is similar to the function of the step-down converter, but it is multiplied by $(1 + n + n_d)$. The voltage increase factor depends on the value of the transformation factor of the autotransformer. These parameters also affect the overvoltages of the components of the autotransformer forward-flyback converter. Therefore, both parameters must be chosen carefully to minimize overvoltages in the converter components.

During operation, direct energy transfer occurs in the autotransformer forward-flyback converter. The output power is determined by the expression:

$$P_{out} = U_{out}\cdot I_{out} = \left(1+n+n_d\right)\cdot T\cdot U_{in}\cdot I_{out} = T\cdot U_{in}\cdot I_{out} + \left(n+n_d\right)\cdot T\cdot U_{in}\cdot I_{out} = P_n + P_m. \tag{4}$$

The ratio between the power transmitted by the magnetic field P_m and the power transmitted directly by P_n is calculated from expression (4):

$$\frac{P_m}{P_n} = n + n_d. \tag{5}$$

Thus, the percentage share of direct and magnetic transfer power is kept constant regardless of the output power and the ratio of output to input voltage. These power percentages depend only on the transmission values of n and n_d. This fact differs from other series-connected converters, such as series-inverting, where the higher the ratio of the output voltage to the input voltage, the lower the percentage of forward power transferred.

The percentage ratios P_n, P_m relative to the output power are defined as:

$$P_n = \frac{1}{1+n+n_d}\cdot P_{out}; \tag{6}$$

$$P_m = \frac{n+n_d}{1+n+n_d}\cdot P_{out}. \tag{7}$$

Thus, the smaller the gear ratio, the smaller the percentage of power that is magnetically processed by the autotransformer. Therefore, lower gear ratios are desirable for higher efficiency. However, because low values of the transformation factor imply high voltage loads and a lower voltage rise factor, a trade-off between the percentage of direct power transfer, voltage loading and voltage rise factor must be reached to achieve an optimal design.

For the calculation, let's take a solar power plant with an average power of 100 kW. In the DMPPT architecture, the choice of central inverter and PV panel is crucial. The inverter will fix the circuit voltage, while depending on the characteristics of the PV panel, the circuit will consist of different number of PV panels. The characteristics of the PV panel are also very important for the design of the DC converter. The FREESUN LVT FS0100 from Power Electronics can be used as a central inverter. For this inverter, the nominal input voltage is 600 V, so it will also be the circuit voltage U_k. On the other hand, the PV panel SKJ60P6L from Silicon, capable of generating up to 225 W, was chosen.

Once the circuit voltage is set and the PV panels are selected, there are many options for configuring the PV panels. The chosen distribution of PV panels for a medium capacity solar power plant consists of a total of 450 PV panels distributed in 25 circles with 18 PV panels in each.

As shown in Fig. 1, the shadow effect in the PV panel changes the current-voltage characteristic of the PV cells, and can also drastically reduce the power produced by the PV panel. In addition, depending on the number and position of the shaded panels, as well as the percentage of shading, the characteristics of the PV panel will change.

The paper considers three options for shading PV panels. In the first option, there are no shaded PV panels, so all PV panels in the circuit generate maximum power. For the second option, the percentage of shaded PV panels is 25 %, and for the third option, it is 30 %. Assuming that all PV panels generate maximum power regardless of the shading condition, the input voltage and power of the converter are established. The output power of a DC-DC converter in a series-connected DMPPT architecture, in which the circuit voltage is fixed by the central inverter, depends on the generated power of the PV panels connected to the same circuit.

$$U_{out\_i} = U_k \cdot \frac{P_{f\_i}}{P_k}, \tag{8}$$

where P_k is the power generated by the entire circuit; P_{f_i} is the power generated by the analyzed PV panel.

The shading effect involves a reduction in voltage and power at the point of maximum power. The values obtained for the photovoltaic panel depending on the percentage of shaded modules are shown in Table 1.

Table 1 – The shading effect of the photovoltaic panel

Parameter	Panel option 1 (100 % / 0 %)		Panel option 2 (75 % / 25 %)		Panel option 3 (70 % / 30 %)	
	unshaded	shaded	unshaded	shaded	unshaded	shaded
Output power P_{out}, W	225	–	225	67.5	225	67.5
Input voltage U_{in}, V	29.3	–	29.3	15	29.3	15
Output voltage U_{out}, V	33.3	–	40.4	12.12	42.19	12.66
Circuit current I_k, A	6.75	–	5.57	5.57	5.33	5.33

As can be seen from Table 1, regardless of the converter topology, the higher the percentage of shaded PV panels, the less power can be produced. Increasing the efficiency of the converter means that more energy can be produced at the solar plant through the use of autotransformer forward-flyback converter.

The main features of the proposed converter are high efficiency and the ability to both increase and decrease the output voltage relative to the input voltage.

Conclusions

On the basis of the conducted research, the following conclusions can be drawn:

– the advantage of the maximum power distributed tracking photovoltaic installations is that the PV panels are isolated from each other, reducing the impact of negative phenomena on power generation;

– the main component of the topology of autotransformer forward-flyback converter, due to which the efficiency of the converter increases, since only part of the energy is processed magnetically;

– the output power of forward-flyback converter in a series-connected DMPPT architecture depends on the generated power of PV panels connected to the same circuit, with the ability to either step up or step down the output voltage relative to the input.

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АНАЛІЗ ТОПОЛОГІЇ АВТОТРАНСФОРМАТОРНОГО ПРЯМОХОДОВОГО ПЕРЕТВОРЮВАЧА ДЛЯ ФОТОЕЛЕКТРИЧНОЇ ПАНЕЛІ

Представлено аналіз перетворювача, який контролює лишечастину вихідної потужності фотоелектричної системи. Розглянуто архітектуру розподіленого моніторингу максимальної потужності, яка є одним з найбільш перспективних рішень для подолання недоліків, пов'язаних з мінливою енергоефективністю фотоелектричних панелей. Представлено топологію автотрансформаторного прямоходового перетворювача постійного струму для фотоелектричних панелей. Показано принцип роботи перетворювача і протікання струму в колі під час комутації. У послідовно з'єднаній архітектурі DMPPT, денапруга контуру фіксується центральним інвертором, отримано методику розрахунку вихідної потужності перетворювача в залежності від потужності, що генерується фотоелектричними панелями, підключеними до контуру. Розраховано потужність, що генерується затінювальною стінкою фотоелектричної панелі.

Ключові слова: *автотрансформатор, ККД, прямоходовий перетворювач, фотоелектрична панель, втрати потужності, сонячна електростанція.*

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