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A NOVEL MULTIPHASE BOOST CONVERTER WITH HIGH ENERGY EFFICIENCY

J. Perduľak, research, Ing., post-grad., D. Kováč, research, Prof. Ing., Prof.
Technical University of Košice
Park Komenského, 3, 04200, Košice, Slovak Republic
E-mail:dobroslav.kovac@tuke.sk, jan.perdulak@tuke.sk
V. Melnykov, post-grad.
Kremenchuk Mykhailo Ostrohradskyi National University
vul. Pershotravneva, 20, 39600, Kremenchuk, Ukraine
E-mail: scenter@kdu.edu.ua

This article describes a topology of multiphase boost converter with high energy efficiency. There are added two more parallel legs in compare with conventional boost converter with one leg. Appropriate control algorithm of switches allows take the photovoltaic output energy one of these three parallel legs in every moment. The simulation results are obtained to verify the theoretical properties of multiphase boost converter.

Key words: boost converter, photovoltaic, energy efficiency.

Introduction. There are more and more increasing demands for the energy stocks and energy self-sufficient of the countries in these days. The logical consequence of this situation is increasing prices of non-renewable sources of energy.

Usage the renewable sources of energy can solve this situation. On the present the photovoltaic has a dominant position in using of renewable sources of energy. Photovoltaic (PV) is the direct conversion of light into electricity in form of direct current electricity. Usually the DC/DC converters are used to convert this direct electrical power form one level to another. There are many types of materials which are used to make of the PV modules. The main problem of these materials is low conversion efficiency. The conversion efficiency is from 5 % (a-Si) to 25 % - 30 % (GaAs) [1].

To-days efficiency of the soft switching DC/DC converters is very well. It is moving around the 97 %. But on the other hand the energy efficiency is not good in comparison with above mentioned converter efficiency.

This paper propose multiphase boost converter with high energy efficiency. The high energy efficiency is ensured by adding two more parallel legs to the conventional boost converter with one leg. The suitable algorithm of switches control in particular legs ensures that the almost whole PV output energy from the PV panel is effective utilized.s

Problem statement. Verification of theoretical assumes of proposed multiphase boost converter with high energy efficiency by simulation attempts. The simulation results were created by using program OrCAD Capture CSI.

Experimental part and result obtained. The conventional topology of single-phase boost converter is shown on fig.1. It consist from inductor *L*, diode *D*, switch *S* and one capacitor *C* on the output of the boost converter.

The proposed topology of multiphase boost converter is on fig.2. The multiphase boost converter has in comparison with the conventional boost converter with one leg two more parallel legs with two inductors (L_2, L_3), two rectifier diodes (D_{21}, D_{31}) and two switches (S_{21}, S_{31}). There are also three auxiliary switches S_{12} – S_{32} on the converter input, which connected the input voltage U_{IN} to the load *Z* and three auxiliary diodes D_{12} – D_{32} which serve as freewheeling diodes. The freewheeling diodes D_{12} – D_{32} return the inductor storage energy W_{L1} – W_{L3} back to the load *Z* after the switches S_{11} – S_{31} respectively S_{12} – S_{32} are turned off.

This converter allows the effective utilize of energy delivered form the solar cell. Appropriate control algorithm of switches allows take the PV output energy one of its three parallel legs in every moment.

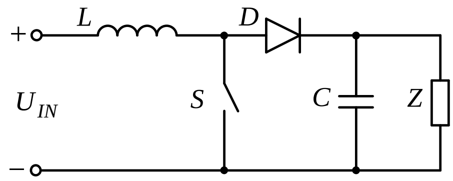

Figure 1 – Conventional topology of single-phase boost converter

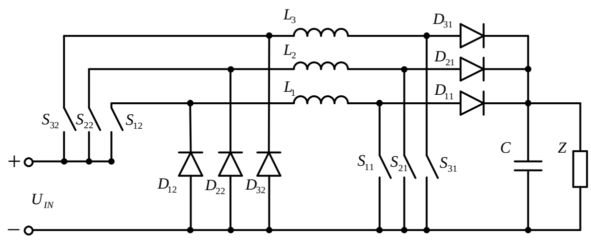

Figure 2 – Proposed multiphase boost converter.

Principle of operation: The function of conventional boost converter with one leg is well known. When the switch *S* is turn on the energy from the input is accumulate in form of magnetic filed in the inductor *L*. This energy is delivered to the output after switch *S* is turn off. The average value of the output voltage $U_{OUT(AV)}$ in continuous conduction mode (CCM) is:

$$U_{OUT(AV)}=\frac{1}{1+z}U_{IN}. \qquad (1)$$

Where duty cycle "z" is ratio between time when the switch *S* is turn on and the period *T*, z = t_1/T. The theoretical waveforms are shown on fig. 3. This process can be repeated three time because three parallel legs are present in proposed multiphase converter which allow effective utilize of delivered energy from solar cell as it was above mentioned.

The proposed multiphase boost converter has 6 operating cycles within each period. The corresponding operation waveforms are shown on fig.4.

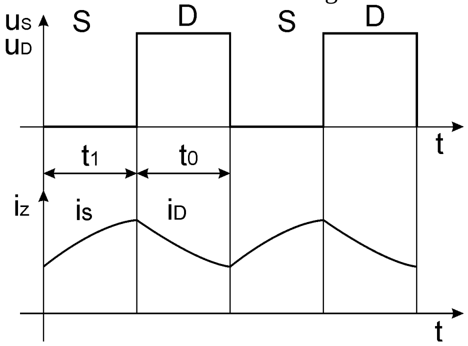

Figure 3 – Theoretical waveforms of conventional boost converter with one leg

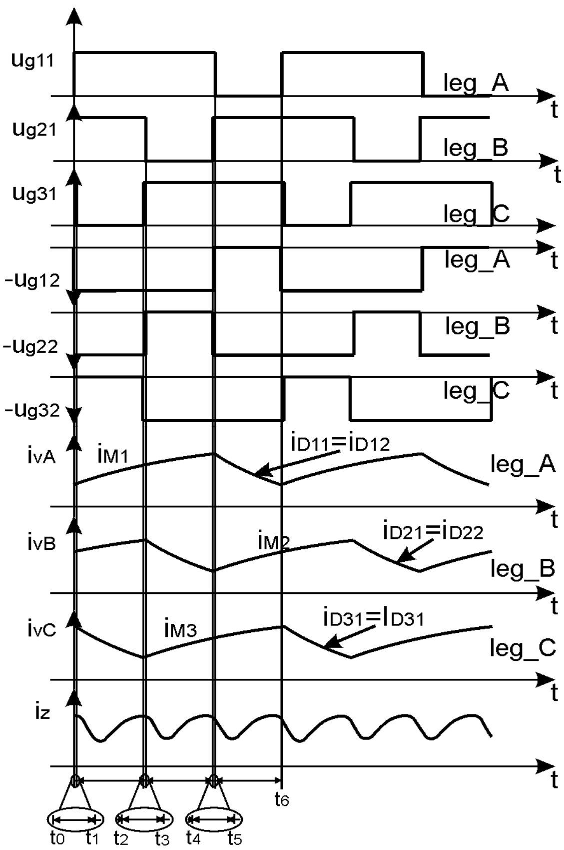

Figure 4 – Theoretical waveforms of proposed multiphase converter

Mode 1($t_0 - t_1$): The switches S_{11} and S_{12} (leg A) are turned on at time t_0. The energy in form of magnetic field begins to accumulate in inductor L_1. The diode D_{12} is reverse biased so the whole input current is closed in loop $+U_{IN} - S_{12} - L_1 - S_{11} - -U_{IN}$. The inductor voltage $u_{L1}(t)$ linear increase:

$$u_{L1}(t) = U_{IN} = L_1 \frac{di_{L1}(t)}{dt}. \quad (2)$$

The current flow through inductor L_1, switches S_{11} and S_{12} is:

$$i_{S11}(t) = i_{S12}(t) = i_{L1}(t) = \frac{1}{L_1}\int_{t0}^{t1} u_{L1}(t)dt + I_{L1}(t_0) = \\ = \frac{U_{IN}}{L_1}(t_1 - t_0) + I_{L1}(t_0). \quad (3)$$

The inductor current exponentially increase from initial value I_{L1} to the maximum value I_{L1max} (which reach at time t_5) with time constant $\tau_1 = L_1/R$.

The other switches S_{21}, S_{31}, S_{22} and S_{32} are turned on, too, so the current delivered to the load is zero $i_Z(t) = 0$ because all three legs are short-circuited in this short time interval.

The currents in legs *B* and *C* and the load current $i_Z(t)$ are:

$$i_{S21}(t) = i_{S22}(t) = i_{L2}(t) = \frac{1}{L_2}\int_{t0}^{t1} u_{L2}(t)dt + I_{L2}(t_0) = \\ = \frac{U_{IN}}{L_2}(t_1 - t_0) + I_{L2}(t_0); \quad (4)$$

$$i_{S31}(t) = i_{S32}(t) = i_{L3}(t) = \frac{1}{L_3}\int_{t0}^{t1} u_{L3}(t)dt + I_{L3}(t_0) = \\ = \frac{U_{IN}}{L_3}(t_1 - t_0) + I_{L3}(t_0); \quad (5)$$

$$i_z(t) = i_{D11}(t) + i_{D21}(t) + i_{D31}(t) = \\ = i_{D12}(t) + i_{D22}(t) + i_{D32}(t) = 0. \quad (6)$$

Mode 2 ($t_1 - t_2$): The switches S_{31} and S_{32} are turned off simultaneously in time t_1. The inductor energy W_{L3} is delivered through decoupling diode D_{31} to the load *Z*. The current in leg C exponentially decrease. The polarity of inductor voltage $u_{L3}(t)$ is reversed so the diode D_{32} is in on-state. The inductor energy W_{L3} through the diode D_{32} is delivered back to the load *Z* and don't return to the source of input voltage U_{IN} as it is in case of using conventional boost converter with one leg. In this case the diode D_{32} serves as freewheeling diode. There is no request recuperation energy back to the source. This fact belongs to the one of the many advantages of this solution. The output energy or more precisely output current $i_Z(t)$ is closed in loop $L_3 - D_{31} - Z - D_{32}$ and back to L_3. The inductor voltage $u_{L3}(t)$ is

$$u_{L3}(t) = -U_Z = -L_3 \frac{di_{L3}(t)}{dt}. \quad (7)$$

The current flow through inductor L_3 and diodes D_{31} and D_{32} is:

$$i_{D31}(t) = i_{D32}(t) = i_{L3}(t) = \frac{1}{L_3}\int_{t1}^{t2} u_{L3}(t)dt + I_{L3}(t_1) = \\ = -\frac{U_Z}{L_3}(t_2 - t_1) + I_{L3}(t_1). \quad (8)$$

the load current $i_Z(t)$:

$$i_z(t)=i_{D31}(t)=i_{D32}(t). \tag{9}$$

Mode 3 (t_2 – t_3): The switches S_{31} and S_{32} are turned on at time t_2. Energy in the form of magnetic field begins to accumulate in inductor L_3 (leg C). The diode D_{32} is reverse biased. The input current is closed in loop $+U_{IN}$ – S_{32} – L_3 – S_{31} – $-U_{IN}$. The inductor voltage $u_{L3}(t)$ is:

$$u_{L3}(t)=U_{IN}=L_3\frac{di_{L3}(t)}{dt}. \tag{10}$$

the inductor current $i_{L3}(t)$ and currents flow through switches $i_{S31}(t)$ and $i_{S32}(t)$ are:

$$\begin{aligned}&i_{S31}(t)=i_{S32}(t)=i_{L3}(t)=\frac{1}{L_3}\int_{t2}^{t3}u_{L3}(t)dt+I_{L3}(t_2)=\\&=\frac{U_{IN}}{L_3}(t_3-t_2)+I_{L3}(t_2).\end{aligned} \tag{11}$$

The inductor current exponentially increase with time constant $\tau_3 = L_3/R$. The switches S_{11}, S_{21}, S_{12} and S_{22} are still turned on, the current delivered to the load is zero $i_Z(t) = 0$ (all three legs are short-circuited).

The currents in legs *A* and *B* respectively and the load current $i_Z(t)$ are:

$$\begin{aligned}&i_{S11}(t)=i_{S12}(t)=i_{L1}(t)=\frac{1}{L_1}\int_{t2}^{t3}u_{L1}(t)dt+I_{L1}(t_2)=\\&=\frac{U_{IN}}{L_1}(t_3-t_2)+I_{L1}(t_2);\end{aligned} \tag{12}$$

$$\begin{aligned}&i_{S21}(t)=i_{S22}(t)=i_{L2}(t)=\frac{1}{L_2}\int_{t2}^{t3}u_{L2}(t)dt+I_{L2}(t_2)=\\&=\frac{U_{IN}}{L_2}(t_3-t_2)+I_{L2}(t_2);\end{aligned} \tag{13}$$

$$\begin{aligned}&i_z(t)=i_{D11}(t)+i_{D21}(t)+i_{D31}(t)=\\&=i_{D12}(t)+i_{D22}(t)+i_{D32}(t)=0.\end{aligned} \tag{14}$$

Mode 4 (t_3 – t_4): The switches S_{21} and S_{22} are turned off at time t_3. The inductor energy W_{L2} begins to deliver through diode D_{21} to the load *Z*. The polarity of inductor voltage $u_{L2}(t)$ is reversed so the diode D_{22} is in on-state. The output current $i_Z(t)$ is enclosed in the loop L_2 – D_{21} – R – D_{22} – and back to the L_2. The inductor voltage $u_{L2}(t)$ is:

$$u_{L2}(t)=-U_Z=-L_2\frac{di_{L2}(t)}{dt}. \tag{15}$$

The current flow through the inductor L_2, diodes D_{21}, D_{22} and the load current are:

$$\begin{aligned}&i_{D21}(t)=i_{D22}(t)=i_{L2}(t)=\frac{1}{L_2}\int_{t3}^{t4}u_{L2}(t)dt+I_{L2}(t_3)\\&=-\frac{U_Z}{L_3}(t_4-t_3)+I_{L2}(t_3);\end{aligned} \tag{16}$$

$$i_z(t)=i_{D21}(t)=i_{D22}(t). \tag{17}$$

Mode 5 (t_4 – t_5): At this time the switches S_{21} and S_{22} are turned on. As in the previous cases the energy in form of magnetic field begins to accumulate in inductor L_2 (leg B). The current is closed in loop $+U_{IN}$ – S_{21} – L_2 – S_{22} – $-U_{IN}$. The diode D_{22} is reverse biased. The inductor voltage $u_{L2}(t)$ is:

$$u_{L2}(t)=U_{IN}=L_2\frac{di_{L2}(t)}{dt}. \tag{18}$$

The current flow through the inductor L_2 and switches S_{21} and S22 is:

$$\begin{aligned}&i_{S21}(t)=i_{S22}(t)=i_{L2}(t)=\frac{1}{L_2}\int_{t4}^{t5}u_{L2}(t)dt+I_{L2}(t_4)=\\&=\frac{U_{IN}}{L_2}(t_5-t_4)+I_{L2}(t_4).\end{aligned} \tag{19}$$

The inductor current $i_{L2}(t)$ exponentially increase with time constant $\tau_2 = L_2/R$. The switches S_{11}, S_{31}, S_{12} and S_{32} are still turned on and the current delivered to the load is zero $i_Z(t) = 0$ (all three legs are short-circuited).

The currents in legs *A* and *C* respectively and the load current $i_Z(t)$ are:

$$\begin{aligned}&i_{S11}(t)=i_{S12}(t)=i_{L1}(t)=\frac{1}{L_1}\int_{t4}^{t5}u_{L1}(t)dt+I_{L1}(t_4)=\\&=\frac{U_{IN}}{L_1}(t_4-t_5)+I_{L1}(t_4);\end{aligned} \tag{20}$$

$$\begin{aligned}&i_{S31}(t)=i_{S32}(t)=i_{L3}(t)=\frac{1}{L_3}\int_{t4}^{t5}u_{L3}(t)dt+I_{L3}(t_4)=\\&=\frac{U_{IN}}{L_3}(t_4-t_5)+I_{L3}(t_4);\end{aligned} \tag{21}$$

$$\begin{aligned}&i_z(t)=i_{D11}(t)+i_{D21}(t)+i_{D31}(t)=\\&=i_{D12}(t)+i_{D22}(t)+i_{D32}(t)=0.\end{aligned} \tag{22}$$

On the assumption that the values of all three inductors L_1, L_2, L_3 and resistance *R* in all three legs are the same then:

$$\tau_1=\tau_2=\tau_3=\frac{L}{R}. \tag{23}$$

Mode 6 (t_5 – t_6): In this last mode the switches S_{11} and S_{12} are turned off. The energy of inductor W_{L1} is delivered to the load *Z* through diode D_{11}. The output current $i_Z(t)$ is enclosed in the loop L_1 - D_{11} – Z – D_{12} – and back to the L_1. The inductor voltage $u_{L1}(t)$ is:

$$u_{L1}(t)=-U_Z=-L_1\frac{di_{L1}(t)}{dt}. \tag{24}$$

The current flow through the inductor L_1, diodes D_{11}, D_{12} and the load current $i_Z(t)$ are:

$$\begin{aligned}&i_{D11}(t)=i_{D12}(t)=i_{L1}(t)=\frac{1}{L_1}\int_{t5}^{t6}u_{L1}(t)dt+I_{L1}(t_5)=\\&=-\frac{U_Z}{L_1}(t_6-t_5)+I_{L1}(t_5).\end{aligned} \tag{25}$$

$$i_z(t)=i_{D11}(t)=i_{D12}(t). \tag{26}$$

Simulation results: The simulation model of multi-phase boost converter fig.5 was created in program OrCAD Capture CSI to verify its theoretical properties. The power MOSFET was used as a co-operating switches. Parameters:

switching frequency	- f_S= 50kHz,
inductance	- $L_1 = L_2 = L_3$ = 500uH,
input voltage	- U_{IN} = 10V,
output voltage	- U_Z = 12V,
duty cycle	- z = 0,67.

Fig. 6 shows the inductor currents $i_{L1}(t)$, $i_{L2}(t)$, $i_{L3}(t)$, and diode currents $i_{D11}(t)$, $i_{D12}(t)$, $i_{D21}(t)$, $i_{D22}(t)$, $i_{D31}(t)$, $i_{D32}(t)$ in particular legs. It can be seen that after turned-on of co-operating transistors in given leg the inductor begin to accumulate energy in form of magnetic field. This energy is consequently delivered to the load *Z* till these couples of transistors are turned-off.

Fig. 7 shows switching-duty cycle of main transistors M_{11}, M_{21} and M_{31} in particular legs and the load current $i_Z(t)$. The load current $i_Z(t)$ is equal to the current of particular leg in every instant of time. There are three neglectable instant of time when the load current $i_Z(t)$ is zero because in these three time intervals are all three legs short-circuited.

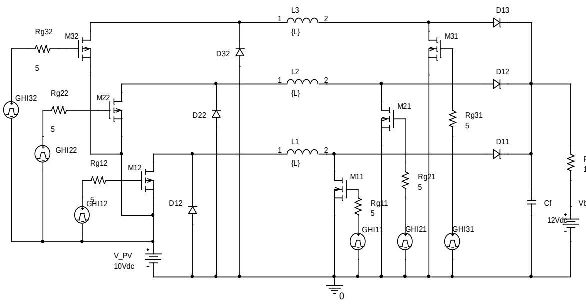

Figure 5 – Simulation model of proposed multiphase boost converter

Fig.8 shows overall load current $i_Z(t)$ at different values of input voltage U_{IN} namely 2V, 4V, 6V, 8V, 10V and 12V (upper part of fig. 8.). From the detail plotting (lower part of fig.8.) it can be seen that the load current $i_Z(t)$ works in CCM for the whole range of input voltages U_{IN}.

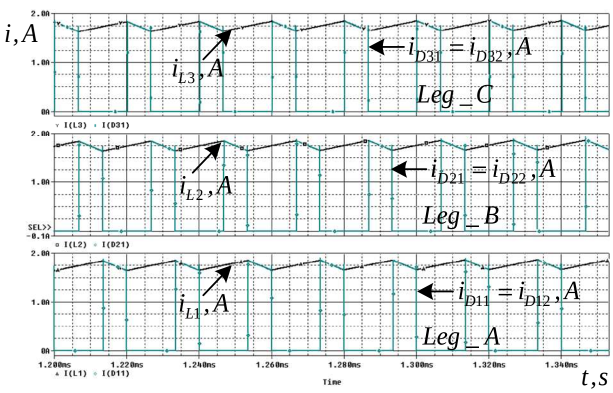

Figure 6 – waveforms of inductor currents i_{L1}, i_{L2}, i_{L3}, and diode currents i_{D11}, i_{D12}, i_{D21}, i_{D22}, i_{D31}, i_{D32}

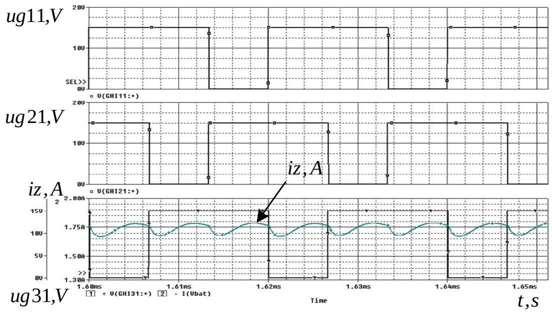

Figure 7 – Waveforms of gate voltage of transistors $u_{g11}(t)$, $u_{g21}(t)$ and $u_{g31}(t)$ and load current $i_Z(t)$

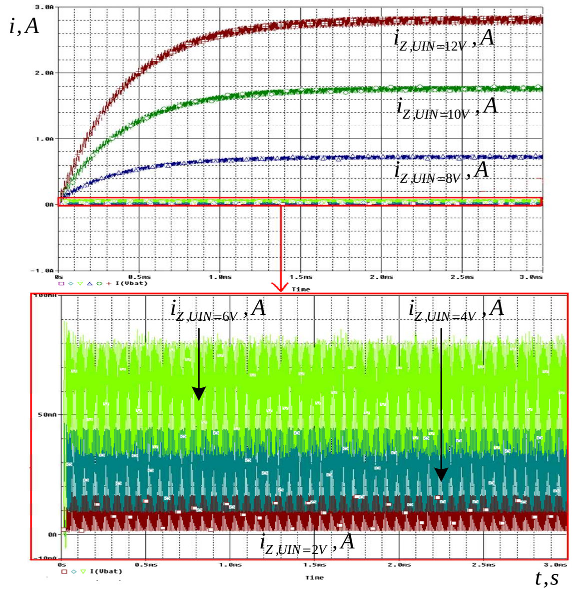

Figure 8 – Load current i_Z at different values of input voltage U_{IN}

The peak-to-peak values of load ripple current Δi_Z are Δi_Z =160 mA for the maximum simulation input voltage U_{IN} = 12V and Δi_Z =15 mA for the minimum simulation input voltage U_{IN} =2V, fig. 9.

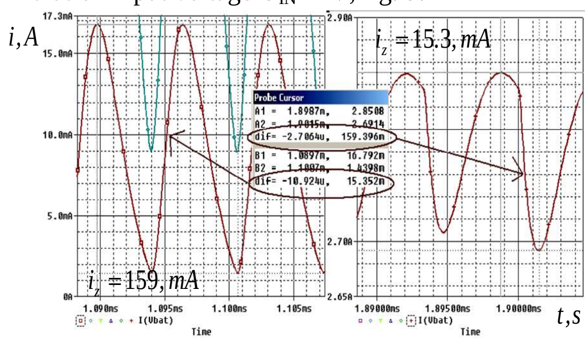

Figure 9 – Load ripple current $i_Z(t)$ for the maximum input voltage U_{IN} = 12V (left waveform) and for the minimum input voltage U_{IN} = 2V (right waveform)

Conclusions. The most popular material was used to make the solar cell is silicium (Si). The *Si* is also major factor in long-term energy recovery and high cost of PV cells. One way to reduce the long –term energy recovery and so high cost of PV cells is proposed multiphase boost converter. This new concept of proposed converter ensures of utilize the full range of energy supplied from the solar cell.

The simulation results confirm the theoretical assumes. The energy efficiency of proposed multiphase converter is very high because the output PV energy is continually delivered to the load by means of three phases of multiphase converter.

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МНОГОФАЗНЫЙ ПОВЫШАЮЩИЙ ПРЕОБРАЗОВАТЕЛЬ С ВЫСОКИМ ЭНЕРГЕТИЧЕСКИМ КОЭФФИЦИЕНТОМ ПОЛЕЗНОГО ДЕЙСТВИЯ

Я. Пердуляк, асп., Д. Ковач, к.т.н., проф.
Технический университет Кошице
Парк Коменского, 3, 04200, Кошице, Словакия
E-mail:dobroslav.kovac@tuke.sk, jan.perdulak@tuke.sk
В. А. Мельников, асп.
Кременчугский национальный университет имени Михаила Остроградского
ул. Первомайская, 20, 39600, г. Кременчуг, Украина
E-mail: scenter@kdu.edu.ua

Описана конфигурация многофазного повышающего преобразователя с высоким энергетическим КПД. В отличие от традиционных схем, повышающих преобразователей с одной электрической ветвью, были добавлены две параллельные электрические ветви. Соответствующий алгоритм управления переключателями позволяет получать выходную энергию фотогальванического элемента по одной из трёх параллельных ветвей в каждый момент времени. Получены результаты моделирования для проверки теоретических свойств многофазных повышающих преобразователей.

Ключевые слова: повышающий преобразователь, фотогальванический элемент, энергетический КПД.

БАГАТОФАЗНИЙ ПІДВИЩУВАЛЬНИЙ ПЕРЕТВОРЮВАЧ З ВИСОКИМ ЕНЕРГЕТИЧНИМ КОЕФІЦІЄНТОМ КОРИСНОЇ ДІЇ

Я. Пердуляк, асп., Д. Ковач, к.т.н., проф.
Технічний університет Кошице
Парк Коменського, 3, 04200, Кошице, Словаччина
E-mail:dobroslav.kovac@tuke.sk, jan.perdulak@tuke.sk
В. О. Мельников, асп.
Кременчуцький національний університет імені Михайла Остроградського
вул. Першотравнева, 20, 39600, м. Кременчук, Україна
E-mail: scenter@kdu.edu.ua

Описана конфігурація багатофазного підвищувального перетворювача з високим енергетичним ККД. На відміну від традиційних схем підвищувальних перетворювачів з одним електричним колом, було додано ще два паралельні електричні кола. Відповідний алгоритм керування перемикачами дозволяє отримувати вихідну енергію фотогальванічного елемента по одній з трьох паралельних гілок у кожен момент часу. Отримано результати моделювання для перевірки теоретичних властивостей багатофазних підвищувальних перетворювачів.

Ключові слова: підвищувальний перетворювач, фотогальванічний елемент, енергетичний ККД.