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SIX PHASE BOOST CONVERTER WITH HIGH EFFICIENCY OF ENERGY CONVERSION

D. Kováč, J. Perduľak
Technical University of Košice
Park Komenského, 3, Košice, 04001, Slovak Republic. E-mail: dobroslav.kovac@tuke.sk, jan.perdulak@tuke.sk

This article introduce a novel concept of boost converter with high efficiency of energy conversion. This new concept allows effective utilization of energy from photovoltaic solar cell. The effective utilization of energy is ensured by adding five parallel legs to the conventional boost converter with one leg. Appropriate algorithm of switches control allows to take the photovoltaic output energy one of these six parallel legs in every moment. The simulation model has been built and the simulation results obtained to verify the theoretical properties of multiphase boost converter. The suitable algorithm of switches control ensures that almost whole photovoltaic output energy from the photovoltaic panel is effective utilized.

Key words: multiphase boost converter, photovoltaic, SLPS interface, energy conversion, CCM mode.

ШЕСТИФАЗНИЙ ПІДВИЩУЮЧИЙ ПЕРЕТВОРЮВАЧ З ВИСОКОЮ ЕФЕКТИВНІСТЮ ПЕРЕТВОРЕННЯ ЕНЕРГІЇ

Д. Ковач, Я. Пердуляк
Технічний університет Кошице
Парк Коменского, 3, м. Кошице, 04001, Словаччина. E-mail: dobroslav.kovac@tuke.sk, jan.perdulak@tuke.sk

Представлено новий принцип підвищуючого перетворювача з високою ефективністю перетворення енергії, що дозволить ефективно використовувати енергію фотогальванічних сонячних комірок. Ефективне використання енергії досягається шляхом додавання п’яти паралельних гілок до звичайного підвищуючого перетворювача з одним ланцюгом. Ефективний алгоритм керування перемикачами дозволяє отримувати енергію з виходу фотогальванічного елементу з кожного з шести паралельних ланцюгів у будь-який момент часу. Побудовано математичну модель для симуляції роботи даного перетворювача та отримано результати симуляції для перевірки теоретичних властивостей багатофазного підвищуючого перетворювача. Ефективний алгоритм керування перемикачами гарантує, що майже вся енергія виходу фотогальванічного елементу сонячної батареї ефективно використовується.

Ключові слова: багатофазний підвищуючий перетворювач, фотогальваніка, SLPS інтерфейс, перетворення енергії, CCM-режим.

PROBLEM STATEMENT. There are more and more increasing demand 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 like for instance oil.

This situation can be solved by using the renewable sources of energy. On the present the photovoltaic (PV) has a dominant position. Photovoltaic 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 from one level to another.

This paper presents the novel concept of multiphase boost converter with high efficiency of energy conversion. The high efficiency of energy conversion is ensured by adding five 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.

EXPERIMENTAL PART AND RESULTS OBTAINED. Fig. 1. explains the problem of efficiency of energy conversion. The impinging sun energy P_{INsun} is converted by PV module direct to the electric energy. According to the material which PV module is build this conversion efficiency moving from 5 % (a-Si) to 30 % (GaAs). The output PV energy P_{OUT_PV} equals the input energy to the converter P_{IN_con}:

$$P_{OUT\_PV} = P_{IN\_con}. \quad (1)$$

Only a part of this input energy P_{IN_con} is drawn by the converter system. The converter works in switching mode with any set value of duty cycle z. According to the set value of duty cycle z, the real amount of input energy to the converter is:

$$P_{IN\_con}{}^{*} = P_{IN\_con}.z\,. \quad (2)$$

It can be seen that the real amount of input energy to the converter $P_{IN\_con}{}^{*}$ is less that the P_{IN_con} because the duty cycle z is theoretically moving from 0 to 1.

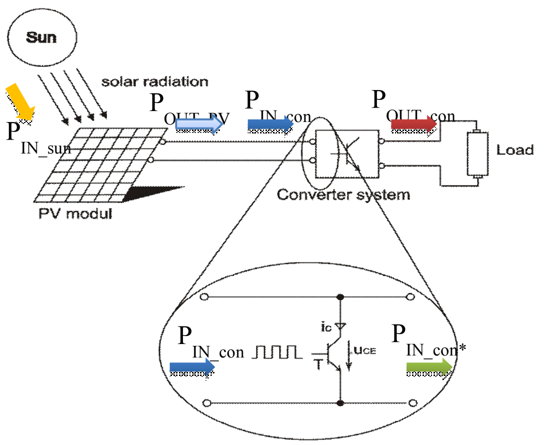

Figure 1 – Overview at efficiency of energy conversion

The three different efficiencies we can define as:

– the conversion efficiency of PV module:

$$\eta_{PV} = \frac{P_{OUT\_PV}}{P_{IN\_sun}}; \qquad (3)$$

– the converter efficiency:

$$\eta_{con} = \frac{P_{OUT\_con}}{P^{*}_{IN\_conv}}; \qquad (4)$$

– the efficiency of energy conversion:

$$\eta_E = \frac{P_{OUT\_con}}{P_{OUT\_PV}}, \qquad (5)$$

where P_{OUT_con} is the output converter energy.

Nowadays, the efficiency of the soft switching DC/DC converters $\eta_{con}$is very well. It is moving around the 97%. But on the other hand the efficiency of energy conversion η_E is in comparison with converter efficiency η_{con} much lower. This fact belongs between one of major factor of long-term energy recovery and high cost of PV modules. One way to reduce the long –term energy recovery and so high cost of PV cells is proposed multiphase boost converter which ensures the equality of converter efficiency η_{con} and the efficiency of energy conversion η_E:

$$\eta_E = \eta_{con} \quad . \qquad (6)$$

THE PROPOSED CONCEPT OF MULTIPHASE BOOST CONVERTER. Fig. 2 shows the conventional topology of single-phase boost converter. It consists of 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 in fig. 3. The multiphase boost converter has, in comparison with the conventional boost converter with one leg, five more parallel legs with five inductors (L_2 - L_6), five rectifier diodes (D_{21} - D_{61}) and five switches ($S_{21} – S_{61}$). There are also six auxiliary switches $S_{12} – S_{62}$ on the converter input. The auxiliary switches $S_{12} – S_{62}$ ensure the connection of the input voltage U_{IN} to the load *Z*. The topology of multiphase converter is also complemented by six auxiliary diodes $D_{12} – D_{62}$ which serve as freewheeling diodes. The freewheeling diodes $D_{12} – D_{62}$ return the inductor storage energy $W_{L1} – W_{L6}$ back to the load *Z* after the particular complementarily switches $S_{a1} – S_{a2}$ are turned off (where a ∈ <1 - 6>).

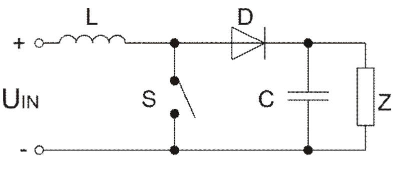

Figure 2 – Convention topology of boost converter

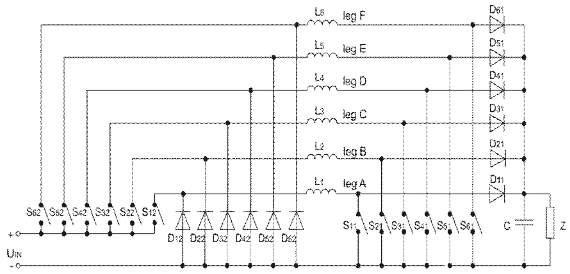

Figure 3 – Multiphase boost converter

This multiphase converter allows the effective utilization of energy delivered form the PV module. Appropriate control algorithm of switches allows take the PV output energy one of its six parallel legs in every moment.

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

$$U_{OUT(AV)} = \frac{1}{1+z} U_{IN}, \qquad (7)$$

where duty cycle "*z*" is ratio between time when the switch *S* is turned on and the period *T*, $z = t_{on(s)}/T$. Fig. 4 shows the theoretical waveforms of single phase boost converter.

This described process can be repeated six times because six parallel legs are presented in proposed multiphase boost converter which allows effective utilization of delivered energy from PV module as was mentioned above.

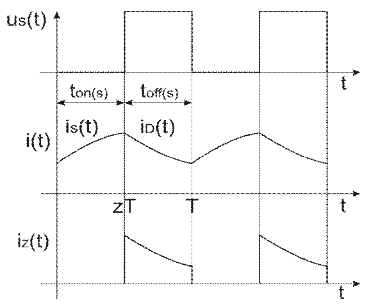

Figure 4 – Theoretical waveforms of conventional boost converter

The proposed multiphase boost converter has 6 operating cycles within each period. The corresponding operation waveforms are shown in Fig. 5.

Mode 1 (t_0–t_1): The switches S_{11} and S_{12} (leg A) are turned on at the 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 $+U_{IN} – S_{12} – L_1 – S_{11} – -U_{IN}$. In this mode

the switches S_{51}, S_{52} (leg E) and S_{61}, S_{62} (leg F) are in on-state. The input energy is delivering to the inductor

L_5 and L_6 in particular legs, too. The switches S_{21}, S_{22} (leg B) and S_{31}, S_{32} (leg C) are in off-state. The inductor energy W_{L2} and W_{L3} is delivered through diodes D_{21} and D_{31} to the load Z. The equivalent equations are:

The inductor voltages $u_{L1}(t)$, $u_{L5}(t)$ and $u_{L6}(t)$ are:

$$u_{L1}(t)=u_{L5}(t)=u_{L6}(t)=U_{IN}=L_{1(5,6)}\frac{di_{L1(5,6)}(t)}{dt}. \quad (8)$$

The inductor voltage $u_{L2}(t)$, $u_{L3}(t)$ and $u_{L4}(t)$ are:

$$u_{L2}(t)=u_{L3}(t)=u_{L4}(t)=-U_{OUT}=L_{2(3,4)}\frac{di_{L2(3,4)}(t)}{dt}. \quad (9)$$

The currents flow through inductors L_1, L_5, L_6 and co-operating switches S_{11} - S_{12}, $S_{51}-S_{52}$, $S_{61}-S_{62}$ are:

$$\begin{aligned} &i_{S11}(t)=i_{S12}(t)=i_{S51}(t)=i_{S52}(t)=i_{S61}(t)=\\ &=i_{S62}(t)=i_{L1}(t)=i_{L5}(t)=i_{L6}(t)=\\ &=\frac{1}{L_{1(5,6)}}\int_{t0}^{t1}u_{L1(5,6)}(t)dt+I_{L1(5,6)}(t_0)=\\ &=\frac{U_{IN}}{L_{1(5,6)}}(t_1-t_0)+I_{L1(5,6)}(t_0). \end{aligned} \quad (10)$$

The currents flow through inductors L_2, L_3, L_4 and couple of diodes $D_{21}-D_{22}$, $D_{31}-D_{32}$, $D_{41}-D_{42}$ are:

$$\begin{aligned} &i_{D21}(t)=i_{D22}(t)=i_{D31}(t)=i_{D32}(t)=i_{D41}(t)=\\ &=i_{D42}(t)=i_{L2}(t)=i_{L3}(t)=i_{L4}(t)=\\ &=\frac{1}{L_{2(3,4)}}\int_{t0}^{t1}u_{L2(3,4)}(t)dt+I_{L2(3,4)}(t_0)=\\ &=-\frac{U_{OUT}}{L_{2(3,4)}}(t_1-t_0)+I_{L2(3,4)}(t_0). \end{aligned} \quad (11)$$

The inductor current $i_{L1}(t)$ exponentially increase from initial value I_{L1} to the maximum value I_{L1max} (reached at the time t_3) with time constant □$_{\iota}$= L_1/R.

Mode 2 (t_1–t_2) and *mode 3 (t_2–t_3)* are the same as *mode1*. Only another co-operating switches S_{21} - S_{22} (leg B, *mode 2*) and S_{31} - S_{32} (leg C, *mode 3*) are turned on, on-state S_{11}, S_{12}, S_{61}, S_{62} (leg A and leg F, *mode 2*) and $S_{11}-S_{12}$, $S_{21}-S_{22}$ (legs A and B, *mode 3*) and off-state $S_{41}-S_{42}$, $S_{51}-S_{52}$ (legs D and E, *mode 3*) and S_{31}, S_{32}, S_{41}, S_{42} (leg D and leg C, *mode 2*). The corresponding equations are the same. Only subscript are changed.

Mode 4 (t_3–t_4): The switches S_{11} and S_{12} are turned off and S_{41} and S_{42} are turned on the beginning of this mode at the time t_3. The inductor energy W_{L1} begins to deliver through diode D_{11} to the load Z. The polarity of inductor voltage $u_{L1}(t)$ is reversed so the diode D_{12} is in on-state. The output current $i_Z(t)$ is enclosed in the loop $L_1-D_{11}-Z-D_{12}$. The switches S_{21}, S_{22} (leg B) and S_{31}, S_{32} (leg C) are on-state and the input energy is delivering to the inductor L_2 and L_3. The switches S_{51}, S_{52} (leg E) and S_{61}, S_{62} (leg F) are in off-state. The inductor energy W_{L5} and W_{L6} is delivered through diodes D_{51} and D_{61} to the load Z. The equivalent equations are:

The inductor voltages $u_{L4}(t)$, $u_{L2}(t)$ and $u_{L3}(t)$ are:

$$u_{L4}(t)=u_{L2}(t)=u_{L3}(t)=U_{IN}=L_{4(2,3)}\frac{di_{L4(2,3)}(t)}{dt}. \quad (12)$$

The inductor voltages $u_{L1}(t)$, $u_{L5}(t)$ and $u_{L6}(t)$ are:

$$u_{L1}(t)=u_{L5}(t)=u_{L6}(t)=-U_{OUT}=L_{1(5,6)}\frac{di_{L1(5,6)}(t)}{dt}. \quad (13)$$

The currents flow through inductors L_4, L_2, L_3 and co-operating switches $S_{41}-S_{42}$, $S_{21}-S_{22}$, $S_{31}-S_{32}$ are :

$$\begin{aligned} &i_{S41}(t)=i_{S42}(t)=i_{S21}(t)=i_{S22}(t)=i_{S31}(t)=\\ &=i_{S32}(t)=i_{L4}(t)=i_{L2}(t)=i_{L3}(t)=\\ &=\frac{1}{L_{4(2,3)}}\int_{t3}^{t4}u_{L4(2,3)}(t)dt+I_{L4(2,3)}(t_3)=\\ &=\frac{U_{IN}}{L_{4(2,3)}}(t_4-t_3)+I_{L4(2,3)}(t_3). \end{aligned} \quad (14)$$

The currents flow through inductors L_1, L_5, L_6 and couple of diodes $D_{11}-D_{12}$, $D_{51}-D_{52}$, $D_{61}-D_{62}$ are :

$$\begin{aligned} &i_{D11}(t)=i_{D12}(t)=i_{D51}(t)=i_{D52}(t)=i_{D61}(t)=\\ &=i_{D62}(t)=i_{L1}(t)=i_{L5}(t)=i_{L6}(t)=\\ &=\frac{1}{L_{1(5,6)}}\int_{t3}^{t4}u_{L1(5,6)}(t)dt+I_{L1(5,6)}(t_3)=\\ &=-\frac{U_{OUT}}{L_{1(5,6)}}(t_4-t_3)+I_{L1(5,6)}(t_3). \end{aligned} \quad (15)$$

The inductor current $i_{L4}(t)$ exponentially increases with time constant □$_{□}$ = L_4/R.

Mode 5 (t_4–t_5) and *mode 6 (t_5–t_6)* are the same as *mode4*. Only another co-operate switches $S_{61}-S_{62}$ (leg F, *mode 6*) and S_{51} - S_{52} (leg E, *mode 5*) are turned on, on-state S_{31}, S_{32}, S_{41}, S_{42} (leg C and leg D, *mode 5*) and $S_{41}-S_{42}$, $S_{51}-S_{52}$ (legs D and E, *mode 6*) and off-state $S_{11}-S_{12}$, $S_{21}-S_{22}$ (legs A and B, *mode 6*) and S_{11}, S_{12}, S_{61}, S_{62} (leg A and leg F, *mode 5*). The corresponding equations are the same. Only subscript are changed.

If we assume that the average value inductor voltage $U_{L(AV)}$ has to be zero for period T, equation (16), then the average value of the output voltage $U_{OUT(AV)}$ of proposed topology of boost converter in CCM can be easily derived

$$U_{L(AV)}=\frac{1}{T}\int_{0}^{T}u_L(t)dt=0. \quad (16)$$

The average value of the output voltage $U_{OUT(AV)}$ of proposed topology of multiphase boost converter in CCM.

$$U_{OUT(AV)}=\frac{z}{1-z}U_{IN}. \quad (17)$$

It is clear that the minimum setting of value for duty cycle z has to be 0,5 respectively 50 % of period T. If the value of duty cycle z is less that the 0,5 than the average value of the output voltae $U_{OUT(AV)}$ will be smaller than the input voltage U_{IN}. The function of multiphase boost converter will be incorrect in this case.

SIMULATION RESULTS. The simulation model of multiphase boost converter shown in fig. 6 was created in simulation environment OrCAD Capture CSI to verify its theoretical properties. Parameters:

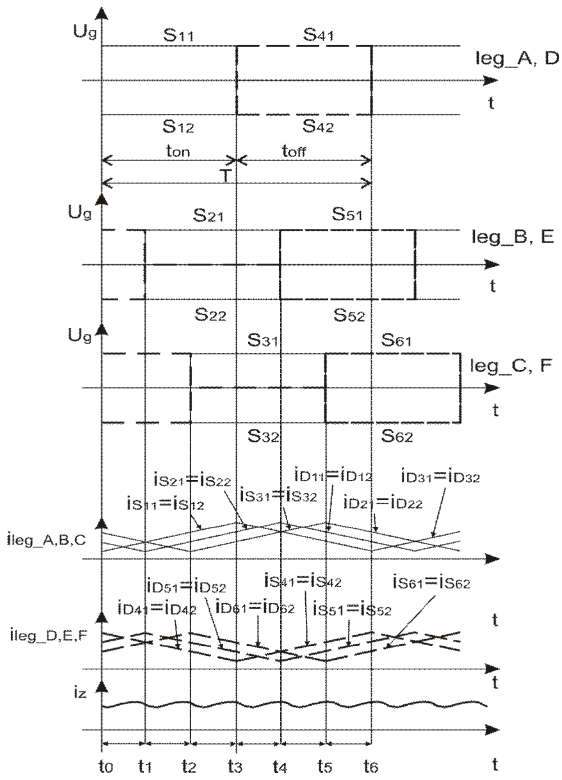

Figure 5 – Theoretical waveforms of proposed multiphase boost converter

– Switching frequency $f_S = 50$ kHz;
– output voltage $U_{bat} = 14$V;
– input voltage $U_{PV} = 10$V;
– inductance $L_1 = L_2 = L_3 = L_4 = L_5 = L_6 = 50$uH;
– capacitance C = 22uF;
– duty cycle z = 0,6.

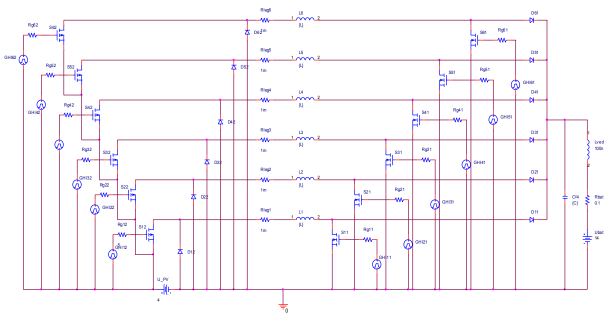

Figure 6 – Simulation model of proposed multiphase boost converter

Fig. 7. shows switching-duty cycle of main transistors S_{11}, S_{12} till S_{61}, S_{62} in particular legs and the load current $i_Z(t)$. The load current $i_Z(t)$ is equal the sum of current in particular legs in every instant of time.

Control structure created in Simulink environment is shown in fig. 8. On this purpose the PSpice SLPS (SimuLink PSpice) simulation environment, supports the substitution of an actual Simulink block with an equivalent analog PSpice electrical circuit, was used.

Fig. 9. shows overview of load current $i_Z(t)$, inductor current $i_L(t)$, input photovoltaic current $i_{PV}(t)$, input and output voltage $u_{out}(t)$ at different values of photovoltaic voltage U_{PV}.

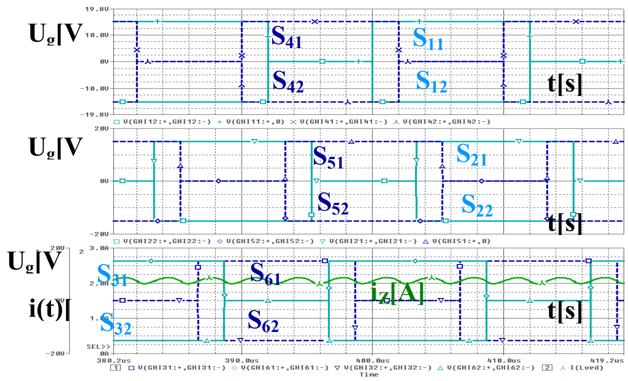

Figure 7 – Waveforms of gate voltage of transistors and load current $i_z(t)$

The PV voltage is moving in range from 12 V to 2 V, with decrement 1 V. In comparison with conventional boost converter with one leg the load current $i_Z(t)$ works in CCM for whole range of input voltages U_{PV} including the minimum value $U_{PV} = 2$ V (Fig. 10).

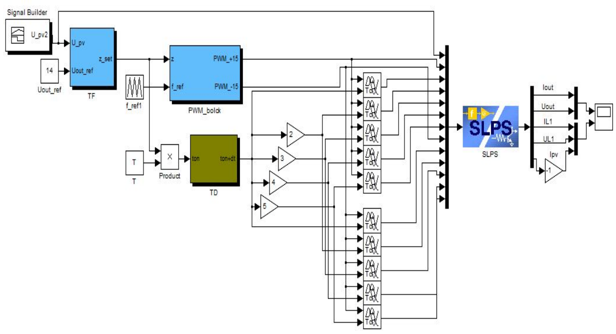

Figure 8 – Simulink model of control structure of six phase boost converter

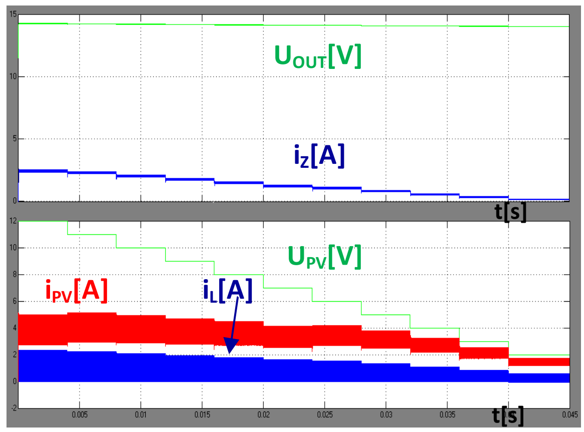

Figure 9 – Waveforms of load current $i_Z(t)$, output voltage U_{OUT} (upper part), inductor and PV currents $i_{PV}(t)$ and $i_L(t)$ and PV voltage (lower part)

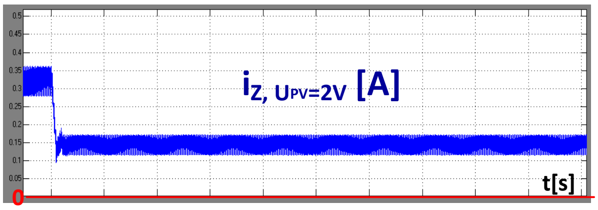

Figure 10 – Load current $i_Z(t)$.

The extended waveforms of inductor current $i_L(t)$, load current $i_Z(t)$ and photovoltaic current $i_{PV}(t)$ are shown in fig.11. The peak-to-peak values of load ripple current □i_Z are very small for whole range of input PV voltage U_{PV}. The peak-to-peak values of load ripple current □i_Z is moving around = 150 mA .

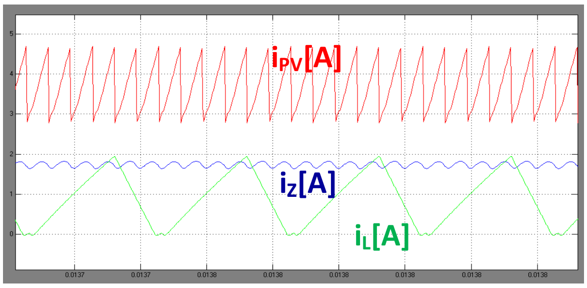

Figure 11 – Extended waveforms of inductor current $i_L(t)$, load current $i_Z(t)$ and photovoltaic current $i_{PV}(t)$

CONCLUSION. The most popular material use to make the solar cell is silicium (*Si*). The *Si* is also one of major factor in long-term energy recovery and high cost of PV moduls. One way to reduce the long –term energy recovery and high cost of PV modules is to use of proposed multiphase boost converter. There is no request for energy recuperation back to the source because the freewheeling diodes are used. This fact belongs between one of the advantages of this solution.

The simulation results confirm the theoretical assumes. The efficiency of energy conversion of proposed multiphase converter is very high because the output PV energy is continually delivered to the load by means of six phases of multiphase converter. This new concept of proposed converter ensures utilization of the full range of energy supplied from the PV module.

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ШЕСТИФАЗНЫЙ ПОВЫШАЮЩИЙ ПРЕОБРАЗОВАТЕЛЬ С ВЫСОКОЙ ЭФФЕКТИВНОСТЬЮ ПРЕОБРАЗОВАНИЯ ЭНЕРГИИ

Д. Ковач, Я. Пердуляк

Технический университет Кошице

Парк Коменского, 3, г. Кошице, 04001, Словакия. E-mail: dobroslav.kovac@tuke.sk, jan.perdulak@tuke.sk

Представлен новый принцип повышающего трансформатора с высокой эффективностью преобразования энергии. Такой принцип позволит эффективно использовать энергию фотогальванических солнечных ячеек. Эффективное использование энергии достигается путём добавления пяти параллельных ветвей к обычному повышающему преобразователю с одной ветвью. Эффективный алгоритм управления ключами позволяет получать энергию с выхода фотогальванического элемента каждой из шести параллельных ветвей в любой момент времени. Построена математическая модель для симуляции работы данного преобразователя, и получены результаты симуляции для проверки теоретических свойств многофазного повышающего преобразователя. Эффективный алгоритм управления ключами гарантирует, что практически вся энергия выхода фотогальванического элемента солнечной батареи эффективно используется.

Ключевые слова: многофазный повышающий преобразователь, фотогальваника, SLPS интерфейс, преобразование энергии, CCM-режим.

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