A Novel Multiphase Boost Converter with High Efficiency of Energy Conversion

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***Abstract* — 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. The simulation model has been built and the simulation results obtained to verify the theoretical properties of multiphase boost converter.**

***Keywords* — multiphase boost converter, photovoltaic, SLPS interface, energy conversion, CCM mode**

I. INTRODUCTION

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.

II. EFFICIENCY OF ENERGY CONVERSION

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), [1]. The output PV energy P_{OUT_PV} equals the input energy to the converter P_{IN_con}.

$$P_{OUT\_PV} = P_{IN\_con} \tag{1}$$

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

$$P_{IN\_con}{}^{*} = P_{IN\_con}.z \tag{2}$$

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.

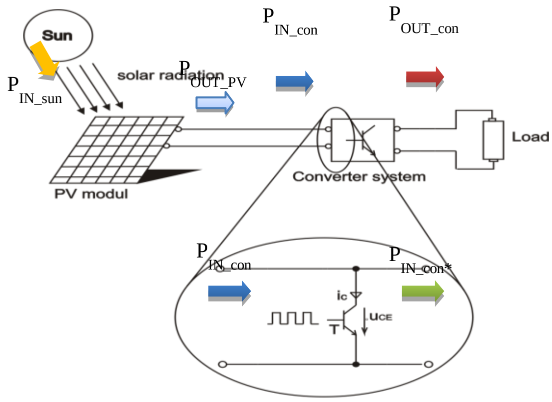

Fig. 1. Overview at efficiency of energy conversion.

The three different efficiencies we can define as:

The conversion efficiency of PV module

$$\eta_{PV} = \frac{P_{OUT\_PV}}{P_{IN\_sun}} \tag{3}$$

The converter efficiency

$$\eta_{con} = \frac{P_{OUT\_con}}{P_{IN\_conv}{}^{*}} \tag{4}$$

The efficiency of energy conversion

$$\eta_{E} = \frac{P_{OUT\_con}}{P_{OUT\_PV}} \tag{5}$$

where P_{OUT_con} is the output converter energy.

Nowadays, the efficiency of the soft switching DC/DC converters η_{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.

III. THE PROPOSED CONCEPT OF MULTIPHASE BOOST CONVERTER

The proposed topology of multiphase boost converter is in fig.2. 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>).

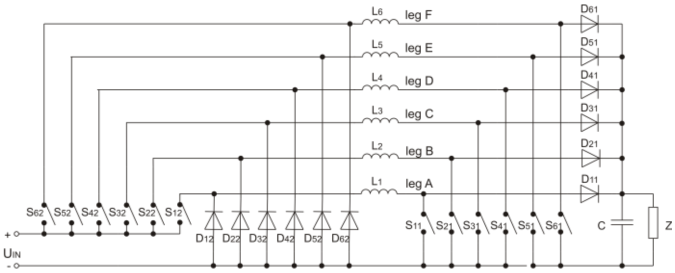

Fig. 2. Multiphase boost converter.

IV. PRINCIPLE OF OPERATION

The proposed multiphase boost converter has 6 operating cycles within each period. The corresponding operation waveforms are shown in fig.3.

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

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

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

$$u_{L2}(t) = u_{L3}(t) = u_{L4}(t) = -U_{OUT} = L_{2(3,4)} \frac{di_{L2(3,4)}(t)}{dt} \tag{7}$$

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

$$\begin{aligned} & i_{S11}(t) = i_{S12}(t) = i_{S51}(t) = i_{S52}(t) = i_{S61}(t) = \\ & i_{S62}(t) = i_{L1}(t) = i_{L5}(t) = i_{L6}(t) = \\ & \frac{1}{L_{1(5,6)}} \int_{t0}^{t1} u_{L1(5,6)}(t)dt + I_{L1(5,6)}(t_0) = \\ & \frac{U_{IN}}{L_{1(5,6)}} (t_1 - t_0) + I_{L1(5,6)}(t_0) \end{aligned} \tag{8}$$

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

$$\begin{aligned} & i_{D21}(t) = i_{D22}(t) = i_{D31}(t) = i_{D32}(t) = i_{D41}(t) = \\ & i_{D42}(t) = i_{L2}(t) = i_{L3}(t) = i_{L4}(t) = \\ & \frac{1}{L_{2(3,4)}} \int_{t0}^{t1} u_{L2(3,4)}(t)dt + I_{L2(3,4)}(t_0) = \\ & -\frac{U_{OUT}}{L_{2(3,4)}} (t_1 - t_0) + I_{L2(3,4)}(t_0) \end{aligned} \tag{9}$$

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 $\tau_1 = L_1/R$.

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

$$u_{L4}(t) = u_{L2}(t) = u_{L3}(t) = U_{IN} = L_{4(2,3)} \frac{di_{L4(2,3)}(t)}{dt} \tag{10}$$

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

$$u_{L1}(t) = u_{L5}(t) = u_{L6}(t) = -U_{OUT} = L_{1(5,6)} \frac{di_{L1(5,6)}(t)}{dt} \tag{11}$$

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

$$\begin{aligned} & i_{S41}(t) = i_{S42}(t) = i_{S21}(t) = i_{S22}(t) = i_{S31}(t) = \\ & i_{S32}(t) = i_{L4}(t) = i_{L2}(t) = i_{L3}(t) = \\ & \frac{1}{L_{4(2,3)}} \int_{t3}^{t4} u_{L4(2,3)}(t)dt + I_{L4(2,3)}(t_3) = \\ & \frac{U_{IN}}{L_{4(2,3)}} (t_4 - t_3) + I_{L4(2,3)}(t_3) \end{aligned} \tag{12}$$

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

$$\begin{aligned} & i_{D11}(t) = i_{D12}(t) = i_{D51}(t) = i_{D52}(t) = i_{D61}(t) = \\ & i_{D62}(t) = i_{L1}(t) = i_{L5}(t) = i_{L6}(t) = \\ & \frac{1}{L_{1(5,6)}} \int_{t3}^{t4} u_{L1(5,6)}(t)dt + I_{L1(5,6)}(t_3) = \\ & -\frac{U_{OUT}}{L_{1(5,6)}} (t_4 - t_3) + I_{L1(5,6)}(t_3) \end{aligned} \tag{13}$$

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 (14), then the average value of the output voltage $U_{OUT(AV)}$ of proposed topology of boost converter in CCM can be easily derived.

$$U_{L(AV)} = \frac{1}{T} \int_{0}^{T} u_L(t)dt = 0 \tag{14}$$

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

$$U_{OUT(AV)} = \frac{z}{1-z} U_{IN} \, . \tag{15}$$

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.

V. Simulation Results

The simulation model of multiphase boost converter shown in fig.4 was created in simulation environment OrCAD Capture CSI to verify its theoretical properties.

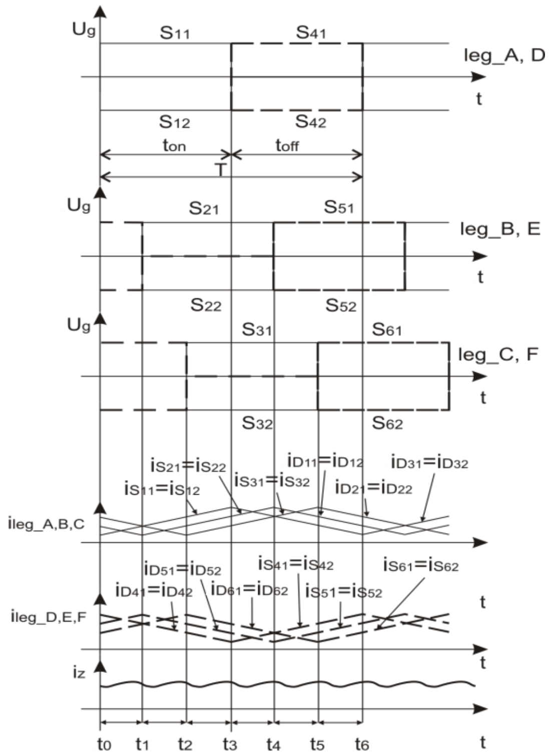

Fig. 3. Theoretical waveforms of proposed multiphase boost converter.

Parameters:

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

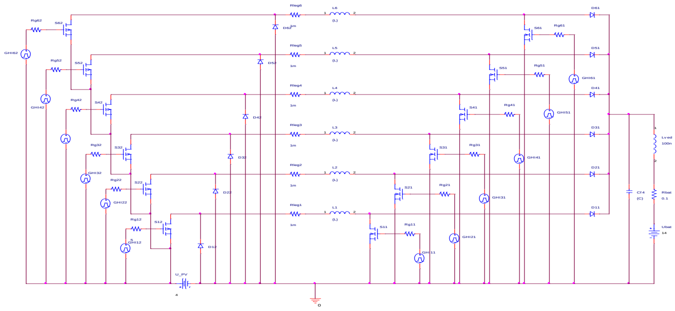

Fig.4. Simulation model of proposed multiphase boost converter.

Fig.5. shows the inductor currents $i_{L1}(t)$ - $i_{L6}(t)$, diode currents $i_{D11}(t)$, $i_{D12}(t)$ - $i_{D61}(t)$, $i_{D62}(t)$ and transistor currents $i_{S11}(t)$, $i_{S12}(t)$ - $i_{S61}(t)$, $i_{S62}(t)$ in particular legs. It can be seen that after turning on co-operating transistors in given leg the inductor begins 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.

Control structure created in Simulink environment is shown in fig.6. 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.

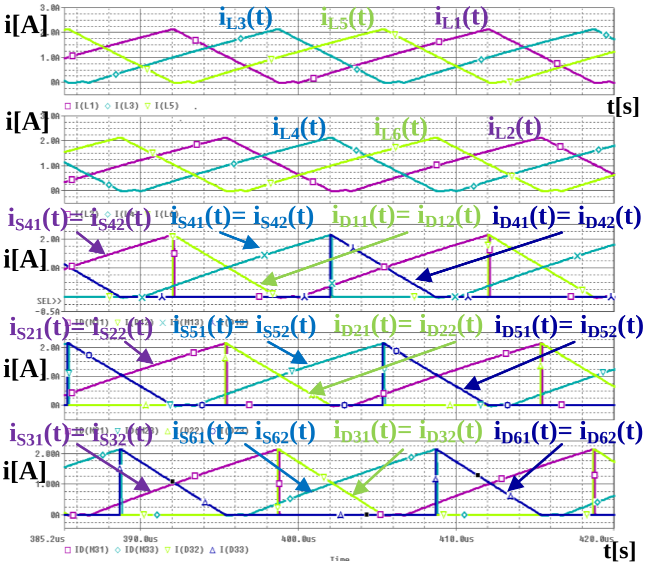

Fig.5. Waveforms of inductor currents $i_{L1}(t)$ till $i_{L6}(t)$, diode currents $i_{D11}(t)$, $i_{D12}(t)$ till $i_{D61}(t)$, $i_{D62}(t)$ and transistor currents $i_{S11}(t)$, $i_{S12}(t)$ till $i_{S11}(t)$, $i_{S12}(t)$.

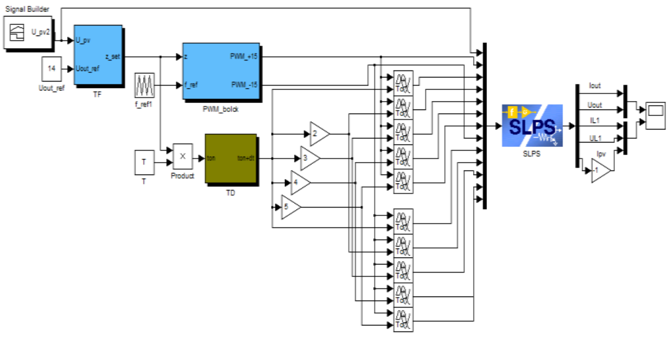

Fig.6. Simulink model of control structure of six phase boost converter.

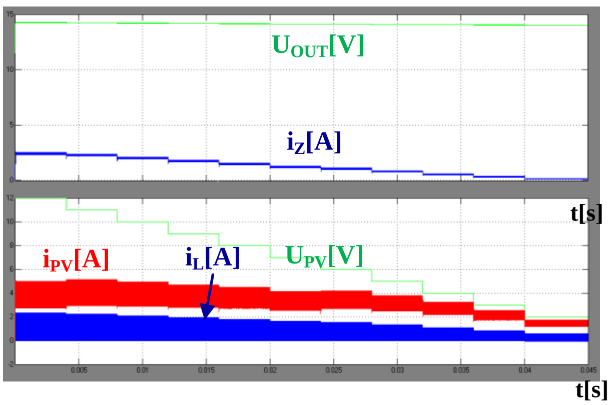

Fig.7. Waveforms of load current $i_Z(t)$, output voltage U_{OUT} (upper part), inductor and PV currents $i_{PV}(t)$ and $i_L(t)$ and PV voltage (lower part).

Fig.7. 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}. The PV voltage is moving in range from 12V to 2V, with decrement 1V. 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} = 2V, Fig.8.

The extended waveforms of inductor current $i_L(t)$, load current $i_Z(t)$ and photovoltaic current $i_{PV}(t)$ are shown in fig.9. The peak-to-peak values of load ripple current Δi_Z are very small for whole range of input PV voltage U_{PV}. The peak-to-peak values of load ripple current Δi_Z is moving around = 150 mA .

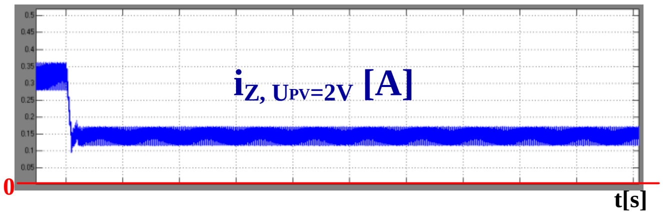

Fig.8. Load current $i_Z(t)$.

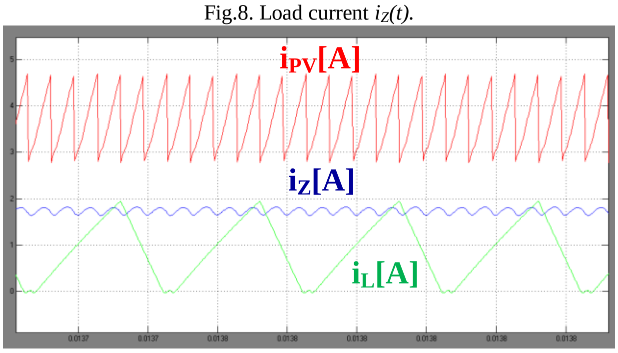

Fig.9. Extended waveforms of inductor current $i_L(t)$, load current $i_Z(t)$ and photovoltaic current $i_{PV}(t)$.

VI. Conclusion

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.

Acknowledgment

The paper has been prepared under support of Slovak grant projects KEGA No. 005TUKE-4/2012, KEGA No.024TUKE-4/2012 and VEGA No. 1/0559/12.

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