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# High-voltage DC converter for solar power station

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**ABSTRACT**

In the article the circuit design solution of DC-DC regulated resonant converter has been proposed for using with hybrid photovoltaic modules which has cooling equipment and solar concentrators in order to maximize electric power generating by such module. By using computer simulation based on multiple iterations algorithm we significantly increase the accuracy of determining the resonance circuit optimal parameters for build up DC–DC converters to work in a wide range of electric powers. Based on optimal values of the resonance LLC scheme parameters, achived by numerical calculation it can be show high values of electrical energy transformation efficiency for photovoltaic energy station equipped with high efficiency hybrid photovoltaic modules. Implementation of microprocessor-based control into design of DC–DC back-boost converters create a new possibility to build control algorithms for increase reliability and conversion efficiency, rapid and precision stabilization of maximum power point, implementation network monitoring of photovoltaic modules, converters itself and the whole photovoltaic station parameters.

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## 1. INTRODUCTION

Solving the problem of photovoltaic power plants ecocnomy competitiveness in comparson with energy produced by carbon-based sources is a prerequisite for solar energy using in growing scale. In order to find the decision of this task, it has been developed the design of hybrid photovoltaic module (PVM) based on single-crystal silicon solar cells with a cooling equipment in order to maximize electric power generating by such module. Using the modules with a cooling equioment in a photovolaic station design leads to below the solar cells (SC) operating temperature [1, 2] which allows to maximize he amount of electricity generated by station and also to increase solar cells lifetime, while equipped modules by solar radiation concentration systems, allows to achieve practically twice increase the power which produced by photovoltaic modules. Assembling of such photovoltaic modules on the tracker, a solar radiation monitoring device, will allow increase the electrical power produced by the photovoltaic station minimum on the 30%. At the same time, development power take-off system on the base of classic elements for conversion direct current produced by a PVM into industrial frequency electricity leads to new problem. The most important component of the power take-off system is the DC-DC back-boost converter, needed to increase the amplitude of produced by the PVM voltage for ensure their minimal losses during transmission and conversion [3, 4]. Since the electrical power produced by the PVM depends from the solar power daytime change, the optimization of

DC-DC converter and the power take-off system design solutions should be carried out taking into account the entire range of converted electrical power. The basic principles of schematic design choice when creating an optimized DC-DC converter with the function of maximum PVM power take-off are to achieve the highest conversion efficiency, ensuring a long operational time and economic ratio of the technical characteristics to the components cost, taking into account a wide range of operating temperatures [5].

Finding out the optimal design of all parts which compose the system to transform energy from PVM into industrial frequency electrical energy should maximize photovoltaic power plants efficiency and give the possibility to reach their competitiveness onto world market by complex of energy and economic parameters. Based on the above mentioned main schematis design principles, it was analyzed and selected schematic designs for DC-DC converter, which will allow to optimize its technical characteristics and increase efficiency [6-8]. The buck boost pulse DC converter is a series connection of the step-down and step-up converters. It is possible to use a common throttle and filter capacitors. In order to increase the efficiency in the buck-boost converter, a bridge circuit with synchronous rectification is often used [9]. The efficiency of the up and down pulse converters takes the maximum value (more than 99%) when the input voltage is equal to the output. Thus, for the step-down converter the efficiency in our case [2] will be maximal at an input voltage of 23 V, and for the step-up converter at an input voltage of 42 V (the minimum and maximum voltage corresponds to the PVM maximum power point take-off [2]). The greater the difference between the input and output voltage, the lower the efficiency. Using step-down converter will be maximally effective at the highest and a step-down converter at the lowest ambient temperature. The serial connection of the step-up and step-down converters allows you to select an input voltage level at which the converter efficiency is greater than 99%, for example a rated input voltage is about 30 V. In this case, the efficiency at the edge of the converter input voltage range will be smaller, but the high efficiency values range will expand. Another advantage is the maximum ripple current in the throttle when using the topology of buck boost pulse DC converter described in [10, 11], which allows to using throttle with a smaller overall size [9].

## 2. RESULTS AND DISCUSSION

### 2.1. Choice of schematic design solution

An example of efficiency dependence for up-, down- pulse controller and buck boost pulse DC converters is shown on Figure 1, and the topology of buck boost pulse DC converter is shown on Figure 2.

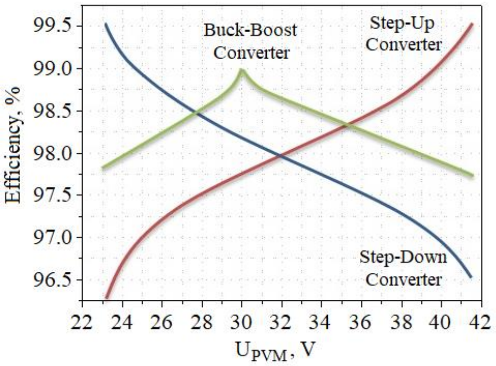


Figure 1. The dependence of the converter efficiency from input voltage

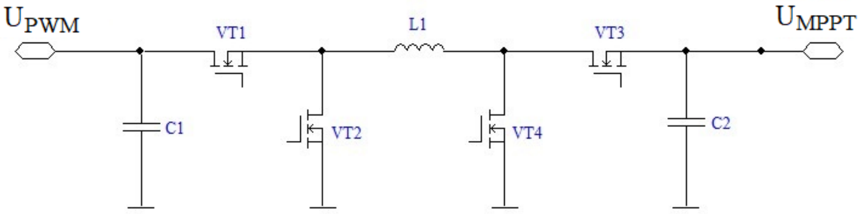


Figure 2. Basic topology of buck boost pulse DC converter

The buck boost pulse DC converter is built using only one inductor and a set of VT1 - VT4 transistors for up and down stages. In this case, to efficiency increase and reduce the load on the passive components in each of operating modes, we need use only its own cascade; the second must be disabled. This is achieved by using 100% duty cycle for VT1 transistor (VT2 off) while using the step-up cascade, and 100% duty cycle for VT3 transistor (VT4 off) when the step-down cascade is active. The buck boost pulse DC converter topology can also be designed by multiphase [12]. The variant of topology, presented on the Figure 2, is the most optimal for PVM maximum power take-off function implementation without galvanic isolation of the input and output circuits. Taking into account the implementation of galvanic isolation, the most optimal solution [13, 14] is the bridge resonance converter topology (BRC), which is shown on Figure 3. Typically, most of modern resonant converters have resonant LLC link structure (serial connection of two inductors and capacitance) [15] and working in zero-voltage switching mode [16, 17] (when used as MOSFET transistors). One of the inductors is represented by the throttle L1, the other by the throttle L2. In practice, the throttle L1 is the sum of transformer TR1 and external throttle (may be absent) inductances and the throttle L2 is the inductance of the transformer TR1 magnetization. Resonant capacitance is represented by capacitor C1. Transistor conductivity losses are proportional to the transformer primary current square, so, despite the larger transistors number in the BRC topology, the transistor conductivity losses are two times lower: the total resistance of the transistor open channel is twice as large and the primary transformer current square is four times less in the BRC topology. At the input voltage from 23 V to 42 V and input power up to 300 W, the most perspective between topologies still BRC. However, in case of multiphase mode implementation, this choice is not so obvious. One from BRC drawback`s is the lack of specialized circuits (PWM controllers) for transistor control, but this is not a disadvantage when implementing digital control system. Significant reactive current in a low-load resonant converter is also not a disadvantage in the unregulated resonant converter design, but in the regulated one is a significant obstacle [18]. Thus, when choosing between a non-resonant and a resonant converter for systems with an input voltage from 23 V to 42 V and a maximum power up 300 W, we should consider the necessity of converter transmission ratio tuning.

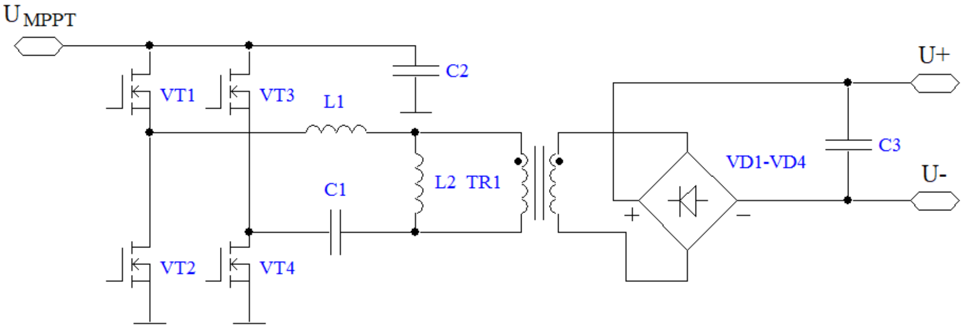


Figure 3. Basic topology of bridge resonant LLC converter

The implementation of maximum power take-off function is usually due to using two-phase two-transistor backflow converter (TTBC) or adjustable resonant LLC converter [19]. The TTBC variant topology is shown on Figure 4. This topology of a single-stroke converter is interesting because it has a higher efficiency than the classical backflow converter due to transformer inductance energy recuperation [20]. Multiphase variant of this topology eliminates another negative property of backflow inverters - the high value of output pulsations. The TTBC topology unambiguously loses by efficiency to the resonant LLC converter, but provides a better implementation of PVM maximum power take-off algorithm due to the almost complete absence of load parameters (600 V -700 V DC inverter) influence on converter`s input parameters. That is, the output DC power supply does not affect the PVM maximum power tracking mode. This feature applies to all backflow converters. Another advantage of this topology is the ability to work on to the short circuited output without high-speed protective circuits using due to unused energy recuperation back into the input circuit [19]. The disadvantages of this topology include the number of phases to reduce the output pulsations and rejection from electrolytic capacitors using, the presence of upper arm transistors control circuit (drivers), as well as the transformers overall dimensions and cost.

In addition, using of adjustable resonant LLC converter allows to obtain higher efficiency values (Figure 5) [21], the disadvantages of controlled conversion include a narrow regulation range and low efficiency at low load when implementing a wider regulation range. However, single cascade using, in comparison with the multi-cascade TTBC scheme, reduces the number of elements and the cost of the converter [22]. At in-series TTBC cascades connection, the total efficiency will be equal to each cascade efficiency product, which means that converter efficiency will be lesser than each of its cascade’s efficiency. Thus, the best circuit design for single-stage converter with the PVM maximum power take-off function and galvanic isolation, in terms of efficiency in a wide input parameters range to the components cost ratio, provides the using of bridge resonant LLC converter topology. However, this topology is most demanding for the correct choice of resonance link parameters and converter operating modes [23].

The proposed schem design ensures the maximally effective converter operation in wide diapasone of operating parameters, and also easy of transistors control system realizatiob, including possibility of specialized integrated circuits using. The high efficiency value minimizes the difficulty with converter cooling. For housing, it is easy to use standart sealed solution from aluminum alloy. Converter operation parameters - maximal values of input power and voltage, was chosen in order to corresponds to single PVM parameters, which allow to using significantly cheap transistors and electronic components of common design, and minimize power components heating.

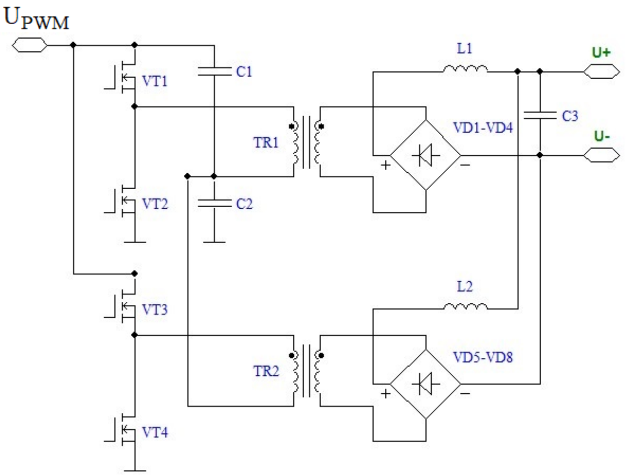


Figure 4. Basic topology of a two-phase two-transistor backflow converter

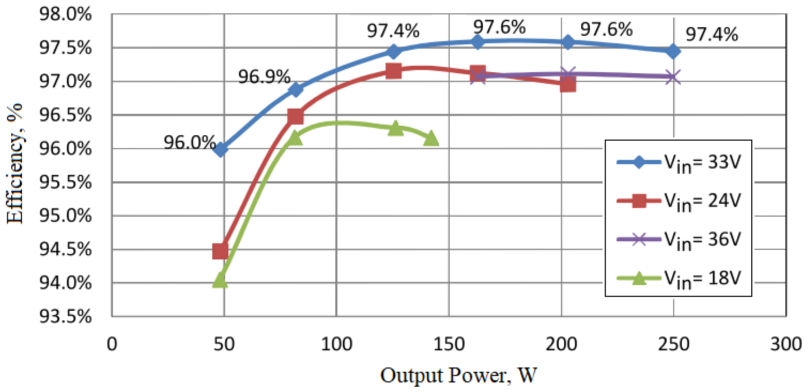


Figure 5. The dependence of bridge resonant LLC converter efficiency from output power at different input voltages

### 2.2. DC-DC back-boost scheme design and parameters calculation

Coefficient of conversion for tunable scheme of bridge converter:

$$G = K \cdot n, \tag{1}$$

Where K is the coefficient of conversion for resonance LLC scheme; n is ratio of turn’s number in secondary and primary windings of the TR1 transformer [24]. Because resonance converter reachs maximum of their efficiency at K = 1, we can obtain n in terms of maximization converter efficiency at their standart operation regime:

$$\boldsymbol{n} = \frac{\boldsymbol{U_{in.nom}}}{\boldsymbol{U_{out.nom}}} = \frac{\mathbf{30}}{\mathbf{630}} = \frac{\mathbf{1}}{\mathbf{21}} \tag{2}$$

In this $U_{in.nom}$ is the nominal voltage value which goes into the converter; $U_{out.nom}$ is the nominal voltage value which goes out from the converter. Coefficient of conversion for resonance LLC scheme will reach their maximum $K_{max}$ in case minimum of input voltage ($U_{in.min}$) and maximum of output ($U_{out.max}$), so the minimum of $K_{min}$ we will have in case of inverse situation with values of working parameters:

$$K_{max} = n \cdot \frac{U_{out.max}}{U_{in.min}} = \frac{1}{21} \cdot \frac{700}{23} \approx 1{,}45 \tag{3}$$

$$K_{min} = n \cdot \frac{U_{out.min.}}{U_{in.max}} = \frac{1}{21} \cdot \frac{600}{42} \approx 0{,}68. \tag{4}$$

In order to obtain the main resonance LLC scheme parameters, we build up the equivalent scheme of our resonance scheme [24, 25]. Coefficient of conversion for such equivalent scheme, can be calculated as follows:

$$K = \left|\frac{U_{in}}{U_{out}}\right| = \frac{F_x^2(m-1)}{\sqrt{(mF_x^2-1) + F_x^2(F_x^2-1)^2(m-1)^2Q^2}} \tag{5}$$

In this $Q = \frac{\sqrt{\frac{L_r}{C_r}}}{R_{ac}}$ is the quality factor; $R_{ac} = \frac{8}{\pi^2} n^{-2} \frac{U_{out}}{I_{out}}$ is value of resistor which serves as a load; $U_{in}$ is voltage value which goes into the converter; $U_{out}$ is voltage value which goes out from the converter; $I_{out}$ is current on the output converter contacts; $F_x = \frac{f_s}{f_r}$ is transistors switching frequency (normalized); $f_s$ – is transistors in converter switching frequency; $f_r = \frac{1}{2\pi\sqrt{L_rC_r}}$ is scheme resonance frequency; $L_r$ is resonance inductance; $C_r$ is resonance capacitance; $m = \frac{L_r+L_m}{L_r}$ is ratio of the total inductance on the circuit input to the resonance inductance; $L_m$ is transformer magnetization inductance.

Minimal value of resistor which serves as a load $R_{ac.min}$ we will have with minimal voltage value which goes out from the converter and maximal power ($P_{in.max}$) produced by converter and also when converter efficiency will reach their maximal value up to 98%:

$$R_{ac.min} = \frac{8}{\pi^2} n^2 \frac{{U_{out.min}}^2}{P_{in.max} \cdot \eta} = \frac{8}{3.14^2} \cdot 0.047619^2 \cdot \frac{600^2}{300 * 0.98} \approx 2.25\ \Omega. \tag{6}$$

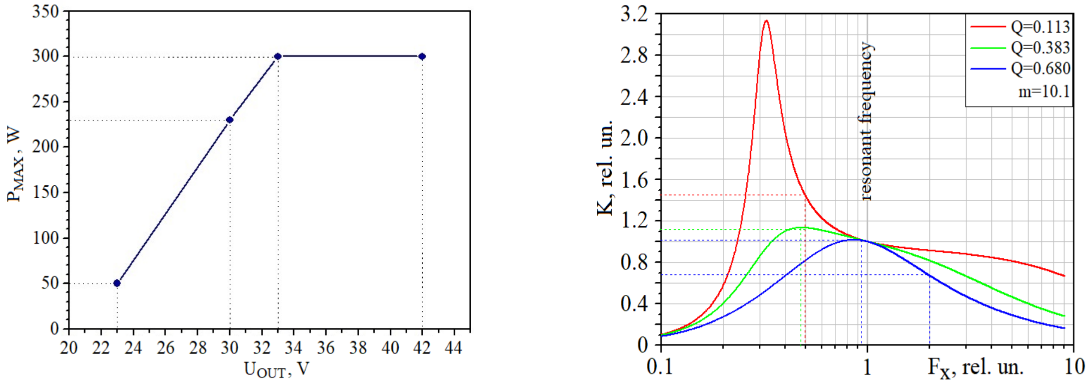
Carried out the correct calculations of the resonance scheme parameters will lead us to optimal converter parameters. For this calculation we use the new algorithm which by the numerous iterations give us the possibility to precision calculate the LLC resonance scheme working parameters [25]. On the base of combination, the preliminary calculation which completed by computer simulation was implemented the possibility to give precision calculation results and minimize the time for such type calculations. Maximal value of voltage which goes into the converter corresponds to module maximum heating at power of illumination 200 W/m$^2$, in this case minimum of power onto converter input ($P_{in.min}$) does not exceed:

$$P_{in.min}\,(23V) \leq\ 23V \cdot I_{in.nom} \cdot \frac{200}{1000} \frac{W}{m^2} = 37{,}6\ W \tag{8}$$

Based on the wide range of operation parameters in DC-DC back-boost converter design, the feature of resonant converter tuning also the dependence of efficiency from LLC circuit parameters, we can define the influence of voltage which goes into the converter on the values of maximum electrical power generated by converter which give the possibility to predict the maximal value of converter efficiency and choose the most effective type of connection to solar module. The specified dependence of the maximal electric power from voltage which goes into the converter has shown on Figure 6, a. From [26] well known that for maximal value of output current we should have the maximal Q. In the other hand the output current maximal values correspond to minimal voltage which goes out from the converter and maximum electric power, generated by convertor. The calculated value of resistor which serves as a load $R_{ac.min}$ = 2.25 Ω matches to maximal value of Q for LLC scheme, and the maximal coefficient of conversion for resonance scheme $K_{max}$ = 1.45 needs to input electric power value up to 50 W and voltage which goes out from the converter up to 700 V. Based on the formulae for *Rac*, the minimum of resistor which serves as a load value $R_{ac.min}$ can be calculated in case of voltage which goes into the converter reaches up to 23 V:

$$R_{ac.min}(23V) = \frac{8}{3.14^2} \cdot 0{,}047619^2 \cdot \frac{600^2}{50 \cdot 0.98} \approx 13.5\ \Omega. \tag{8}$$

Using the above mentioned algorithm, we build diagram and calculate values of resonance scheme parameters for 100 kHz resonance frequency which shown on Figure 6, b and presented in Table 1.



(a) (b)

Figure 6. The dependence of DC-DC converter maximum output power from input voltage (a) and the dependence of LLC circuit transmission coefficient from normalized frequency at given figure of quality values (b)

Table 1. Working parameters of resonance scheme

| $U_{in}$, V | $P_{in}$, W | $K_{max}$ | $K$ | $R_{ac.max}$, Ω | $Q_{max}$ | $F_x$ |
|---|---|---|---|---|---|---|
| 23 | 50 | 1,45 | 3,13 | 13,5 | 0,113 | 0,33 |
| 30 | 230 | 1,11 | 1,134 | 3,995* | 0,383* | 0,48* |
| 33 | 300 | 1,01 | 1,026 | 2,25 | 0,68 | 0,86 |
| 42 | 300 | 0,79 | 1,026 | 2,25 | 0,68 | 0,972 |

*Presented $R_{ac.min}$ matches to maximal voltage which goes out from the converter and $K_{max}$.

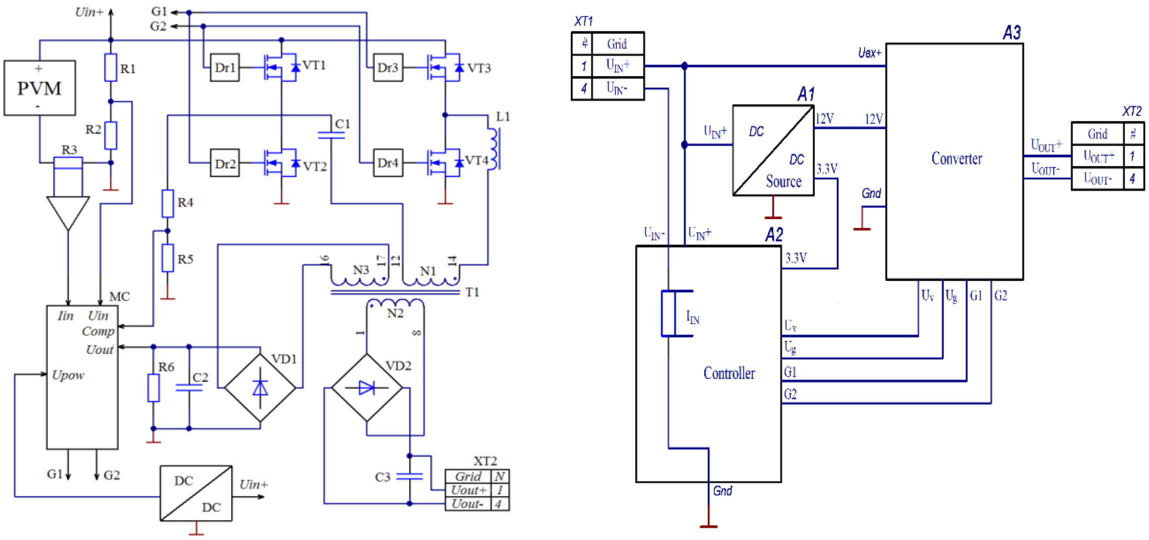
Taking into account the resonance capacitance of 0.94 μF at 110.7 kHz frequency we calculate the resonance inductance - Lr = 2.2 μH and having *m* = 10.1 calculate the transformer magnetization inductance - Lm = 20 μH.

## 2.3. DC-DC converter making

The functional and principal electric scheme of the DC-DC converter shows on Figure 7. Voltage from PVM goes to the converter input and digital microcontroller MC installed to optimize the parameters of converter and for control of transistors switching. The signal from MC goes to VT1 – VT4 transistors gates through Dr.1 – Dr.4 drivers. According to bridge scheme we have a simultaneous transistor switching on every bridge part. Microcontroller and driver powering up by specialized DC converter which ensure stabilizing and stepping-down of input voltage. Using of microcontroller ensures the continuous monitoring of current, generated by module by means of shunt resistance R3 and amplifier, and voltage outgoing from module by using divided scheme based on R1 – R2 resistors. At their G1 and G2 pins the microcontroller generate two impulses which are counter-phases and neede to set up the frequency of transistors switching and establish the delay («dead») time for bridge diagonals switching [27]. Midpoint value of voltage on VT1 - VT2 transistors half-bridge using for implementing adaptive «dead» time principe needed to ensure maximal values of converter efficiency, goes on to microcontroller comparator pins from divided scheme based on R4 - R5 resistors. The VD1 rectifyer connects with N3 winding of transformer connected in order to control the nominal voltage value which goes out from the converter and also it using in algorithmic detection of resonance LLC scheme operating mode to prevent changing their current flow regime into the capacitive. The necessity of such resonance scheme operating regimes control is valuable at converter start and in case of fast changes of voltage value which goes out from the converter – a DC network 600 –700 V.

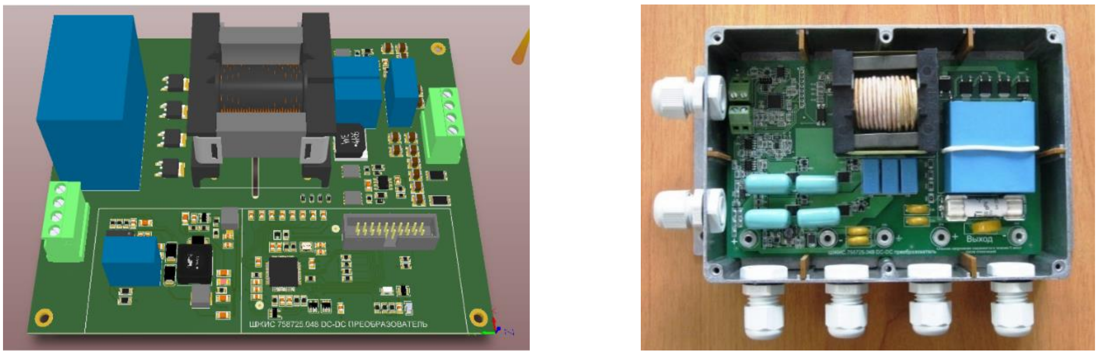
The resonance LLC scheme consists from choke, capacitor and a transformer - L1, C1, T1, respectively. The resonance inductance combines from L1 inductance and T1 scattering inductance. Voltage from transformer output needs to be restifying by scheme on the base of VD2 diode C3 capacitor. After rectifier the DC voltage goes directly on to converter. Hybrid module maximum power point searching and tracking ensured on the base of perturbation and Observation (P&O) algoritm by microcontroller [28, 29]. For implementing this algorithm the microcontroller firstly calculates the PVM putput power, and at second act it makes a small change of converter input resistance through the variation of transistors switching frequency, as a result the voltage on the converter input also changes, and MC carry out the power calculation - if it increase – the MC will continue to changing input voltage in established direction up to the moment when power began to decrease. Using of microcontroller allow to implement a P&O algorithm for searching and tracking the PVM maximum power point, and also to realize adaptive «dead» time, and continious monotoring in order to finding the capacitive nature of the bridge load. Also implementing microcontroller in converter design will allow integrate it into monitoring network by using cable or wireless connection, like RS-485 or ZigBee protocols, in order to continuous monitoring of modules parameters, ensuring information about the failure, etc [30].

Figure 8 shows the DC-DC converter based on proposed schematic design for direct installation on photovoltaic modules, which allow to maximize the efficiency of electricity generation from solar iiradiation.



(a) (b)

Figure 7. Functional electric (a) and principal electric (b) circuit of the DC-DC converter



(a) (b)

Figure 8. Circuit board 3D model (a) and manufactured (b) DC-DC converter

## 3. CONCLUSION

Presented design of regulated resonance converter represents a perspective scheme solution that will allow to obtain maximized efficiency electric energy generation a photovoltaic energy station equipped by hybrid photoenergy modules on the silicon solar cells base. Using the resonance transformation solution make easier the solving of finding out the best combination of back-boost converter parameters which based on resonance scheme in a wide range of input and output electric power. The application of computer simulation based on numerous iterations algorithm allow to establish the optimum resonance LLC scheme parameters values. Using of microcontroller allow to implement an effective algorithm for searching and tracking the hybrid modules maximum power point, and also to realize adaptive «dead» time, and continious monotoring in order to finding the capacitive nature of the bridge load. Also implementing microcontroller in converter design will allow integrate it into monitoring network by using cable or wireless connection, like RS-485 or ZigBee protocols, in order to continuous monitoring of modules parameters and ensuring information about the failure.

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