DEVELOPMENT OF A HIGH-VOLTAGE POWER TAKE-OFF SYSTEM FOR PHOTOVOLTAIC POWER PLANTS
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Abstract
The analysis of operation of a photovoltaic power plant power take-off system equipped with a boost converter is carried out. It is shown that the efficiency of such a system in a wide range of photovoltaic module lighting stands at level of 0.92 while the effectiveness of classical PTO systems does not exceed 0.70. We have developed a circuit diagram of a controlled bridge resonant boost converter with digital control that ensures reliable operation, fast and accurate determination of maximum power point, and the conversion efficiency to 0.96.

Keywords: Photovoltaic module, boost converter, power take-off system, photovoltaic power plant, coefficient of performance.

1. Introduction
In order to generate a maximum electric power by a photovoltaic power plant (PPP), high-performance power take-off (PTO) systems should be used [1] in addition to high-efficiency photovoltaic modules (PVM) equipped with solar radiation concentrators. The most important part of power take-off system system is DC-DC converter which provides boosting a constant voltage generated during photovoltaic module operation for its further efficient transmission and transformation [2, 3]. Thus, since depending on the daily change of solar radiation the electric power generated by the photovoltaic module varies, optimization of constructive solutions for DC-DC converters and power takeoff systems should be carried out taking into account the full range of converted electric power. Optimization of design and technological solutions of all components of solar energy conversion systems in the industrial frequency electric power will improve PPP efficiency and achieve its competitiveness in the domestic and global market per totality of its energy and economic indicators.
Based on the above, the task of creating a highly efficient and cost effective power take-off system in this work was solved through the implementation of three stages. At the first stage we have studied the dependence of the electric power on the intensity of the incident solar radiation. On the basis of these data, at the second stage we have carried out calculations of DC-DC resonant circuit and converter operating parameters, and we have developed DC-DC converter circuit diagram. At the third stage, the analysis of the PTO system operation using DC-DC boost converter was carried out.

2. Experimental technique

Measurement of short-circuit current ($I_{SC}$), open-circuit voltage ($U_{OC}$), operating ($I_o$) and maximum ($P_{MAX}$) capacity and the coefficient of performance (COP) for typical PVM industrial prototypes made in China were carried out at the power of solar radiation from 1000 up to 2000 W / m$^2$, which allows simulating their work when using augmentors. These values were measured by the light load current-voltage characteristics method with use of the bench developed and manufactured by the authors [3] and the block diagram shown in Figure 1.

![Figure 1. Block diagram (a) and appearance (b) of the bench for investigation testing of photovoltaic modules.](image)

The bench for photovoltaic module studying includes: the photovoltaic module under study (1), the control unit (2), pulse light based on xenon flash bulbs (3), the load resistance box (4) with electronic switching through MOSFET-transistors, and the digital oscilloscope intended for registration of the experimental data (5).

We have designed and manufactured the load resistance box for its use in the capacity of a load resistance where individual resistors were switched by using modern MOSFET transistors of IRFZ48Z type having in on-state very low (0.011-0.012 Ohm) and stable channel resistance value so not contributing a substantial interference in the load resistance value even when measuring short-circuit currents. Voltage drop across the load resistance was registered by a digital oscilloscope RIGOL DS1052E having the ability to be connected directly to PC.
The principle of operation of the bench was as follows. Upon pulse irradiation from the light source a photovoltaic module generates a photocurrent which duration of peak value strength approximately corresponds to the basic phase duration of the flash lamp illumination what is about 1 millisecond. Amplitude value of the photocurrent strength dividing into diode component, leakage across a shunt resistor and the peak value of current that flows in the load resistance 4 causes a voltage drop across the load resistance that is registered by the digital storage oscilloscope 5 operating in the gated sweep mode.

To monitor the photovoltaic module temperature during the measurements we connected directly to the photovoltaic module a thermocouple wired to the measuring device MIT-8.10M. Determination and adjustment of the radiation power level on the front surface of the photovoltaic module within the range of 1000-2000 W / m² was carried out using a reference photoelectric converter having a known short-circuit current value upon the emission power of 1000 W / m². Tests by the above procedure were performed sequentially with the radiation power values of 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000 W / m² and repeated for three experimental PVM models.

3. Results and their discussion

3.1 Effect of the radiation power on the photovoltaic module efficiency

Characteristic research results for experimental PVM samples are presented in table 1. Figure 2 shows general graphs constructed on the basis of the data of dependencies for idling voltage, short-circuit current, maximum power and coefficient of performance on the radiation power exposing the front surface of the photovoltaic module.

By the results of the investigation tests of experimental PVM samples we can conclude that for all the samples when the emission intensity was 1500-1800 W / m² there were achieved the value of the open circuit voltage of 37.5 V, value of short-circuit current 11-13 A, value of the maximum power up to 440 W, voltage at the operating point not less than 33 V what provides the coefficient of performance of the photovoltaic module not less than 16.8%.

Table 1 - Output PVM parameters determined during the investigation tests at different radiation power (P_R) exposing the front surface of the photovoltaic module.

<table>
<thead>
<tr>
<th>P_R, W/m²</th>
<th>U_idle, V</th>
<th>I_SC, A</th>
<th>U_OP, V</th>
<th>I_OP, A</th>
<th>P_max, W</th>
<th>COP, %</th>
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<td>32.75</td>
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<td>241.49</td>
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<td>8.11</td>
<td>266.65</td>
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<td>1300</td>
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<td>9.98</td>
<td>33.10</td>
<td>9.58</td>
<td>317.08</td>
<td>16.71</td>
</tr>
<tr>
<td>Radiation Power (W/m²)</td>
<td>Short Circuit Current (A)</td>
<td>Open Circuit Voltage (V)</td>
<td>Maximum Capacity (W)</td>
<td>Coefficient of Performance (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
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<td>15.33</td>
<td>32.74</td>
<td>14.71</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Typical graphs of dependencies of the short circuit current (a), open circuit voltage (b), maximum capacity (c), and coefficient of performance (d) of the photovoltaic module under study on the radiation power exposing its front surface.

It should be noted that the use of experimental PVM models in a low-concentration solar radiation conditions is justified because it is when the radiation power is 1700 W/m² the PVMs under study reach maximum coefficient of performance equal to 16.89%. An additional advantage of using a low-concentration radiation is increase in the maximum power generated by the photovoltaic module to 419 W, that is 1.7 times greater than a predetermined value which is characteristic to classical solar panels. The use of low-concentration solar radiation is an additional argument
in favor of equipping each photovoltaic module by a DC-DC boost converter upon development of a power take-off system (PTO) as the operating current of a photovoltaic module at a radiation power 1700 W/m\(^2\) reaches to 13 A that is almost twice as high as the same amount upon radiation power equal to 1000 W/m\(^2\). In the case of PTO implementation in the traditional way this will either cause additional losses in the connecting wires, or lead to the need for significant investment to equip a photovoltaic power plant by increased section cables.

3.2 Development of DC-DC boost converters for a highly effective power take-off system

When developing a DC-DC boost converter we have used parameters obtained in the course of PVM series study as reference (Table 1).

3.2.1 Calculation of DC-DC resonant circuit and a converter operating parameters

The transmission factor of a controlled bridge resonant converter:

\[ G = K \times n, \] (1)

where

K – the transmission factor of a resonant circuit LLC;

n – the secondary-to-primary turn ratio of the transformer TR1.

The resonant converter has a maximum efficiency at \( K = 1 \); let's compute \( n \) from the condition of maximum efficiency in the converter's nominal operation mode:

\[ n = \frac{U_{\text{in.rated}}}{U_{\text{out.rated}}} = \frac{30}{630} = \frac{1}{21}, \] (2)

where

\( U_{\text{in.rated}} \) - the rated input voltage of the converter;

\( U_{\text{out.rated}} \) - the rated output voltage of the converter.

The transmission factor of a resonant circuit LLC should take the maximum value \( K_{\text{max}} \) when combined minimum input and maximum output voltages and the minimum value \( K_{\text{min}} \) at combination of maximum input and minimum output voltages:

\[ K_{\text{max}} = n \times \frac{U_{\text{out.max}}}{U_{\text{in.min}}} = \frac{1}{21} \times \frac{700}{23} \approx 1.45; \] (3)

\[ K_{\text{min}} = n \times \frac{U_{\text{out.min}}}{U_{\text{in.max}}} = \frac{1}{21} \times \frac{600}{42} \approx 0.68. \] (4)

To calculate the resonant circuit LLC parameters let's use the equivalent circuit for the resonant circuit [4 - 6]. For this equivalent scheme, the resonant circuit LLC transmission factor is described by the expression:
\[ K = \frac{U_{in,ac}}{U_{out,ac}} = \frac{e^{2}f_{0}^{2}(m-1)}{\sqrt{(mF_{0}^{2}-1)+F_{0}^{2}(F_{0}^{2}-1)^{2}+m^{-1}Q^{2}}}, \]  
(5)

Where

\[ Q = \frac{\frac{1}{\sqrt{L_{r}c_{r}}}}{R_{ac}} \quad \text{Q-factor}; \]  
(6)

\[ R_{ac} = \frac{8}{\pi^{2}} \cdot n^{-2} \cdot \frac{U_{out}}{I_{in}} \quad \text{The reduced load resistance}; \]  
(7)

\[ U_{out} \quad \text{Converter output voltage}; \]

\[ I_{out} \quad \text{Converter output current}; \]

\[ F_{x} = \frac{f_{x}}{f_{r}} \quad \text{Normalized transistor switching frequency}; \]  
(8)

\[ f_{r} = \frac{1}{2\pi\sqrt{L_{r}c_{r}}} \quad \text{Resonant frequency for } L_{r}, C_{r} \text{ circuit}; \]  
(9)

\[ L_{r} \quad \text{Resonant inductance}; \]

\[ C_{r} \quad \text{Resonant capacitance}; \]

\[ m = \frac{L_{r}+L_{m}}{L_{r}} \quad \text{Ratio of the total inductance of the input circuit to the resonant inductance}; \]  
(10)

\[ L_{m} \quad \text{Magnetizing inductance of the transformer.} \]

The minimum reduced load resistance \( R_{ac,\min} \) corresponds to the minimum output voltage and maximum input power for the expected maximum coefficient of performance equal to 98%:

\[ R_{ac,\min} = \frac{8}{\pi^{2}} \cdot n^{-2} \cdot \frac{U_{out}}{P_{in,\max}} = \frac{8}{3,14^{2}} \cdot \frac{0,047619^{2}}{300+0,98} \approx 2,25 \text{ (Ohm)}. \]  
(11)

The correct calculation of the resonant circuit allows obtaining the best characteristics of the converter. The algorithm allows for multiple iterations to calculate the required parameters of the resonant circuit LLC.

Using an approximate calculations and updating them with the simulation we can get correct enough results with significant time savings.

The minimum input voltage of DC-DC converter corresponds to a maximum temperature of the photovoltaic converter, and light exposure 200 W / m\(^2\) i.e. an input power of no more than:

\[ P_{in}(23V) \leq 23V \cdot I_{inrated} \cdot \frac{200}{1000} W/m^{2} = 37,6 W. \]  
(13)
Maximum Q-factor value corresponds to the maximum output current. The output current takes a maximum value at the minimum output voltage and a maximum output power.

The value of the given minimum load resistance \( R_{ac\,\text{min}} = 2.25 \, \text{Ohms} \) corresponds to a maximum Q-factor of LLC loop, upon that a maximum value of the resonant circuit transmission factor \( K_{\text{max}} = 1.45 \) is required for the input power of 50 W and an output voltage of 700 V. According to the expression (7) the value of the reduced minimum load resistance \( R_{ac\,\text{min}} \) for input voltage 23 V is determined:

\[
R_{ac\,\text{min}} (23) = \frac{8}{3} \times 0.0476192 \times \frac{600^2}{50 + 0.98} \approx 13.5 \, \text{(Ohms)}.
\]

Data for 100 kHz resonance frequency obtained by the algorithm for calculating the parameters of the resonant circuit through several iterations checked by computer simulation are shown in Table 2. The value of the total input to the resonant circuit inductance ratio \( m = 11 \).

### Table 2 - Parameters of the resonant circuit.

<table>
<thead>
<tr>
<th>( U_{\text{in}}, \text{V} )</th>
<th>( P_{\text{in}}, \text{W} )</th>
<th>( K_{\text{max}} )</th>
<th>( K )</th>
<th>( R_{ac,\text{min}}, \text{Ohm} )</th>
<th>( Q_{\text{max}} )</th>
<th>( F \times \min. )</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>50</td>
<td>1.45</td>
<td>3.13</td>
<td>13.5</td>
<td>0.113</td>
<td>0.33</td>
</tr>
<tr>
<td>30</td>
<td>230</td>
<td>1.11</td>
<td>1.134</td>
<td>3.995*</td>
<td>0.383*</td>
<td>0.48*</td>
</tr>
<tr>
<td>33</td>
<td>300</td>
<td>1.01</td>
<td>1.026</td>
<td>2.25</td>
<td>0.68</td>
<td>0.86</td>
</tr>
<tr>
<td>42</td>
<td>300</td>
<td>0.79</td>
<td>1.026</td>
<td>2.25</td>
<td>0.68</td>
<td>0.972</td>
</tr>
</tbody>
</table>

* The value of \( R_{ac\,\text{min}} \) corresponds to the maximum output voltage and \( K_{\text{max}} \).

By selecting the resonant capacitance value of 0.94 uF at the resonance frequency \( F_r = 110.7 \, \text{kHz} \) we obtain the resonant inductance value \( L_r = 2.2 \, \text{mH} \) and when \( m = 10.1 \) transformer magnetizing inductance \( L_m = 20 \, \text{uH} \).

#### 3.2.2 Development of DC-DC converter schematic diagram

Figure 3 shows a functional diagram of a DC-DC converter. PV module voltage is supplied to the DC-DC converter input. Formation of the converter parameters and transistors switching is carried out by a digital microcontroller \( MC \).

The control signal to the gates of transistors \( VT1 - VT4 \) comes from \( MC \) through drivers \( Dr1 - Dr4 \). Transistors are switched synchronously within each branch of the bridge.
Power supply of drivers and microcontrollers is performed through stabilized auxiliary DC downconverter (SD). MC measures the PVM output current by means of shunt R3 and amplifier, the PVM output voltage through divider based on resistors R1 - R2.

MC at the outputs G1 and G2 generates two antiphase square waves for switching the transistors with the required frequency and time delay between switching bridge diagonals ("dead" time). Voltage in VT1 and VT2 transistors half-bridge mid-point used in determining adaptive "dead" time (minimum sufficient) to reach maximum efficiency of the converter, through the divider based on resistors R4 and R5 is supplied to the comparator Comp MC. Additional transformer winding N3 connected to the rectifier bridge VD1 is used to control the output voltage and, together with a voltage signal from the half bridge midpoint is involved in the algorithm for detection of approaching to the capacitive nature of the resonant circuit LLC current.

Detecting a proximity to the capacitive nature of the resonant circuit current is essential when the converter is started, and at a relatively rapid change in voltage value at the converter output up to 600 V - 700 V of DC network.

![Figure 3. Electrical connections of DC-DC converter.](image)

Photovoltaic module voltage is supplied to DC-DC converter input. Formation of converter parameters and transistors switching are carried out by the digital microcontroller MC. The control signal to the gates of transistors VT1 - VT4...
Kryukov Yu.A* et al. International Journal of Pharmacy & Technology comes from MC through drivers Dr1- Dr4. Transistors within each bridge branch are switched synchronously. Power supply of drivers and microcontrollers is performed through stabilized auxilliary DC downconverter (SD). MC measures PVM output current by means of shunt R3 and amplifier, and PVM output voltage through a divider based on resistors R1 - R2. MC generates at the outputs G1 and G2 two antiphase square waves for switching the transistors with the required frequency and time delay between switching diagonals of the bridge ("dead" time). VT1 and VT2 transistors half-bridge mid-point voltage used in determining an adaptive "dead" time (minimum sufficient) for maximum converter efficiency through the divider based on resistors R4 and R5 is supplied to the comparator Comp MC. Additional transformer winding N3 connected to the rectifier bridge VD1 serves to control the output voltage and, together with a half bridge midpoint voltage signal is used in the algorithm for detection of approaching to capacitive nature of the LLC resonant circuit current. Detecting proximity to the capacitive nature of the resonant circuit current is essential when the converter is started, and at a relatively sharp changes in voltage value at the converter output in 600 V - 700 V DC network. The resonant circuit LLC is formed by an inductor L1, a capacitor C1, and a transformer T1. Resonant inductance includes the inductance of inductor L1 and leakage inductance of the transformer T1. The output voltage from the transformer is supplied to the rectifier formed by a diode bridge VD2 and the capacitor C3. Rectifier output voltage is the output voltage of the converter. Maximum power point tracking (MPPT) of the photovoltaic module is performed by the microcontroller algorithm "Perturbation and observation". [7] The microcontroller calculates converter input power, then changes by a small value the input resistance by changing a transistor switching frequency, thereby the input voltage changes, and then it calculates the power. If power increases the controller continues to change the voltage in the same direction until the power no longer increases. Digital control of the converter allows performing an algorithm for tracking the maximum capacity point for the algorithm "Perturbation and observation", to form the adaptive "dead" time, to detect the current capacitive nature in the bridge load. With use of MC it becomes possible to realize the information wired or wireless network, for example, RS-485 or the ZigBee, to monitor the parameters of photovoltaic modules and converters providing timely information on faults, etc.

3.2.3 Schematic diagram of a DC-DC converter

The converter consists of the functional blocks A1 - A3.

A1.Auxilliary power supply source (PS) is designed to generate 3.3 V stabilized voltage for controller power supply and 12 V voltage for power supply of drivers of the converter transistors.
PS consists of two serial hush cascades of DC pulse down converters without electrical isolation. PS is highly efficient and stabilizes the output voltage over a wide input voltage range.

A2. Controller. 32 bit ARM CortexM-4As is used in the capacity of a microcontroller. After level conversion and filtering, feedback signals are fed to the microcontroller ADC. The current signal from a shunt is amplified by differential amplifier to a desired level and then goes to the ADC. A source of reference voltage ADC is made on the basis of DA6 chip.

Comparators are made on the basis of high-speed integrated circuits LMV7235M5. Transistor control signals are sent through the chain of G1 and G2 to driver inputs.

A3. Schematic diagram of the converter is shown in Figure 6.11. The converter consists of: four transistors MOSFET VT1 - VT4; two half-bridge drivers on chips DA7, DA8; power circuit capacitors $U_{\text{in}}$; resonant circuit LLC with inductor $L_A$, transformer $T_I$, capacitors $C_{46}, C_{47}$; signal rectifier with the diodes $V_D - VD12$; the output rectifier with the diodes $VD13 - VD16$ and capacitors $C_{52}, C_{53}$. High-speed MOSFET transistors with low gate charge and on-resistance of 2.8 mOhms are used in the capacity of bridge transistors. Silicon carbide diodes are applied in the output rectifier what allows significantly to increase the efficiency within the frequency range of transistors switching higher than the resonant frequency due to the absence of reverse recovery losses for diodes on the basis of silicon carbide.

3.3 Analysis of PTO system operation with the use of a DC-DC boost converter

Significant reduction of power losses [8, 9] in PTO can be a result of using in its composition of previously developed DC-DC converters that can reduce currents flowing in the most of PTO and, respectively, and to reduce power losses proportionally to the current square. In the case of PTO construction with use of DC-DC converters, the system will be divided into the following sections where losses in PTO will be observed:

- Wired connection section between the photovoltaic module and DC-DC converter ($P_{\text{cons.PVM-DC}}$);
- Directly DC-DC converter ($P_{\text{cons.DC}}$);
- Wired connection section between DC-DC converter and the inverter through a main control box ($P_{\text{pot.DC-inv}}$);
- Inverter ($P_{\text{pot.inv.}}$).

The computed losses for each of the following sections depending on the photovoltaic module current are shown in Table 3 and Figure 4. The losses in DC-DC converter have been calculated based on the calculated efficiency of such a device constituting 95.8%. As can be seen from the curves, the losses in PTO areas increase with photovoltaic
module current increase, but losses values are significantly less due to lower current values at the section after DC-DC converter. Figure 4 shows two dependencies of losses in the wires from the photovoltaic module to the converter that are characteristic for the wires of different lengths: 25m and 65m, respectively. Total loss of capacity and coefficient of performance for PTO with use of DC-DC boost converters is shown in Figure 5 in comparison with the same parameters obtained for PTO without use of DC-DC converters.

**Table 3 - Loss of power and COP parameters calculated for PPP using DC-DC boost converters.**

<table>
<thead>
<tr>
<th>P.I, W/m²</th>
<th>I_PVM, A</th>
<th>P_cons.PVM-DC, W</th>
<th>P_cons.DC, W</th>
<th>P_cons.DC-Inv, W</th>
<th>P_cons. inv, W</th>
<th>P_cons. total, W</th>
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</table>
Figure 4. The dependence of the calculated value of the power conductor loss in the section PVM - DC-DC converter (a), in the DC-DC converter (b), in conductor of the section DC-DC converter - inverter (c), in inverter (d) due to the photovoltaic module current: 1 - 65m wire; 2 - 25m wire.

Figure 5. Dependence of the calculated power loss value (a) and COP loss (b) of PPP PTO using DC-DC converters (solid line) compared with PPP without DC-DC converters (dotted line)

The results of PTO calculations allow us to conclude that the use in such a system of DC-DC converters can significantly reduce power losses in the PTO and thus improve COP of a system. The above will result in an additional increase in usable power delivered to a consumer through an inverter.

According to Figure 9, a, the total loss of power in such PTO upon radiation power 1700 W / m² will amount 644.6 W which is much less than 6180.8 W being characteristic to a system without DC-DC converters. This will lead to higher PTO efficiency which will increase from 71.0% to a value of 92.5%. It should also be noted that COP remains almost unchanged within wide range of photovoltaic module light exposure what will vary depending on weather and seasonal conditions.

4. Conclusions

Adjustable bridge resonant DC-DC converters designed to optimize power take-off systems allows achieving high conversion efficiency values up to 95.8%.

A high efficiency value is achieved through the use of DC-DC converter digital control, and offers great opportunities to create control algorithms that ensure conversion reliability and efficiency, fast and accurate determination of a maximum power point.

The calculations made for PTO system of an photovoltaic power plant with use of designed DC-DC converters has shown that COP of such a system within wide range of PVM light exposure is level of 92% that is significantly greater than for classical PTO systems which efficiency is level of 70%.
5. Acknowledgment

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