# Resonant DC-DC Converter for Photovoltaic Systems

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***Abstract* — This paper describes a step-up DC-DC converter, which main task is to increase the voltage from a low level drawn from a photovoltaic (PV) panel, to a high controlled level for a connected inverter. The converter also provides an electrical isolation of PV panels from the grid. In the DC-DC converter a resonant LLC topology is used. The converter operates at high switching frequency to achieve small size of the power transformer. The main benefit of this converter is zero-voltage switching (ZVS) of primary MOSFETs and zero-current switching (ZCS) of rectifier diodes over the entire operating range. Advantage of used topology is that the converter can be controlled by a simple 8bit microcontroller (MCU). A laboratory model with maximum 95.5 % efficiency was built to verify properties of the LLC resonant DC-DC converter.**

***Keywords—LLC resonant converter, zero-voltage switching (ZVS), zero-current switching (ZCS)***

## I. INTRODUCTION

In nowadays the consumption of fossil fuels is on its maximum level, and new sources of oil or gas are discovered only rarely. And therefore we must think how we will compensate this deficit. One of options is using renewable power sources. Today the power of water and wind are most used. However with increasing development in photovoltaics the solar energy is more and more used nowadays. This increase is related to increasing efficiency of transformation of solar energy to electrical energy. Now, the common efficiency of PV cells is over 15 %, and in the laboratory was achieved efficiency up to 42 %. Rising demand on a market for photovoltaic is related to reducing cost of PV panels and benefits which many countries offer. In Fig.1 the yearly cumulative installed power of PV panels in Slovakia for years 2005 to 2011 is shown.

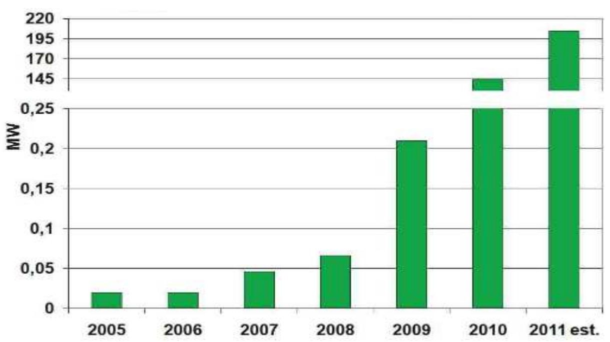


Fig. 1. Cumulative installed power of PV panels for years 2005-2011

For using the energy drawn from PV panels, we need special type of a converter. The type of the converter depends on method how we use PV panels. If system of PV panels and converter is not connected to power grid, we talk about off-grid system. At no-load, the energy obtained from PV panels is usually stored in batteries. If the consumption of energy begins, the converter starts to transfer the energy to the load through the inverter. If the level of power obtained from PV panels is higher than the system can offer, the converter starts to draw the energy from batteries.

Photovoltaic systems connected to an electric grid, called on-grid, are more often used today. In this case special inverters are used, which convert the energy from PV panels directly into the grid.

It is desired to use the renewable energy sources with maximum efficiency. One of the possibilities how to increase the efficiency of a PV system, is to increase the efficiency of the inverter. There are quantities of inverters for PV systems on the market. Some inverters include DC-DC step-up converter, depending on whether the inverter is connected to the string of PV panels with voltage higher than the maximum value of the grid voltage. When a thin film PV panels are used, problem with leakage current will occur. Therefore it must be used a converter with transformer which provides galvanic isolation between PV panels and grid.

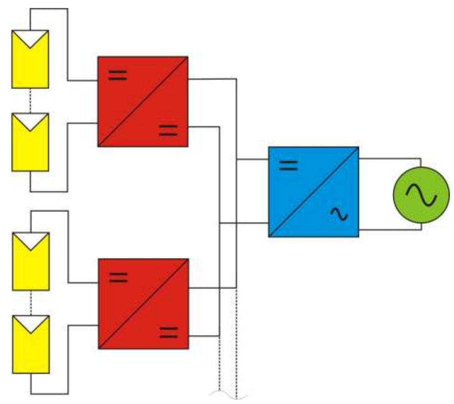

Fig. 2. Topology of converter for photovoltaic system connected to grid

If the line frequency transformer is used, the whole converter will be heavy and bulky. Therefore better solution can be, if transformer is used in DC-DC converter. At a high switching frequency, the power transformer can achieve small size and weight. If there is a second converter in cascade, the overall efficiency will decrease. It is not such a big problem if a DC-DC converter with very high efficiency is used.

It can be used more DC-DC converters in a photovoltaic system to supply an inverter as it is shown in Fig. 2. MPPT (Maximum Power Point Tracking) can be achieved for each PV string.

The described DC-DC converter can operate with input voltage range from 60 V to 100 V. The required output voltage, which is the input voltage for the inverter, is 400 V. The maximum power output is about 600 W.

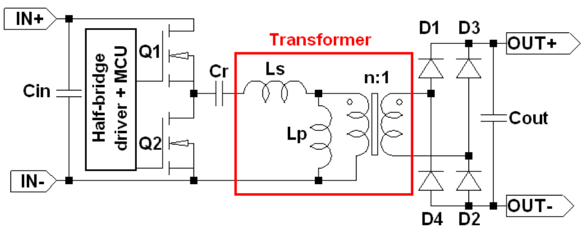


Fig. 3. The principal schema of proposed LLC converter

Considering that it is required to have the high efficiency and an electrical isolation, the series resonant LLC half-bridge converter was chosen [1]. Principal schema of the LLC converter is shown in Fig. 3. It consists of the half-bridge inverter with power MOSFET switches, from which the LLC resonant tank is supplied.

The resonant tank of the converter consists of series inductance $L_S$, parallel inductance $L_P$ and the resonant capacitor $C_R$. On secondary side of the transformer there is a full-bridge rectifier with a filter capacitor $C_{out}$.

## II. Principle of Operation

Power MOSFETs are switched with variable frequency with fixed 50 % duty cycle and no overlapping. The resonant tank has two main resonant frequencies. The higher resonant frequency $f_R$ depends on the series inductance and the resonant capacitor and is calculated by using equation (1). The lower resonant frequency $f_0$ is additionally influenced by the parallel inductance (2). If the switching frequency is higher than $f_R$, the converter operates always in the inductive area. It means that the resonant tank current lags the input voltage square waveform, and therefore switches work under ZVS condition. Below the resonant frequency $f_0$, the resonant tank behaves as a capacitive load. Therefore the resonant tank current leads the input voltage. Switches operate under ZCS condition. The area between frequencies $f_0$ and $f_R$ is split by a borderline to the capacitive and the inductive region. The operating point in this area depends on the load of the converter. When the switching frequency is equal to the resonant frequency $f_R$, the voltage gain of the resonant tank is unit. It means that the converter is independent on the load. At normal operation condition, the operating point should be placed near to this resonant frequency. Fig 4 shows voltage gain curves of the resonant tank for few load conditions. We can see the capacitive region on the left side of the borderline and the inductive region on its right side.

$$f_R = \frac{1}{2\pi\sqrt{L_S C_R}} \quad (1) \qquad f_0 = \frac{1}{2\pi\sqrt{(L_S + L_P)C_R}} \quad (2)$$

$$M(Q, f_N, \lambda) = \frac{1}{\sqrt{\left(1+\lambda-\frac{\lambda}{f_N^{\,2}}\right)^2 + Q^2\left(f_N - \frac{1}{f_N}\right)^2}} \quad (3)$$

$$Q = \frac{\pi^2 Z_0 P_{OUT}}{8n^2 V_{OUT}^{\,2}} \quad (4) \qquad Z_0 = 2\pi f_R L_R \quad (5)$$

$$\lambda = \frac{L_S}{L_P} \quad (6) \qquad f_N = \frac{f_{SW}}{f_R} \quad (7)$$

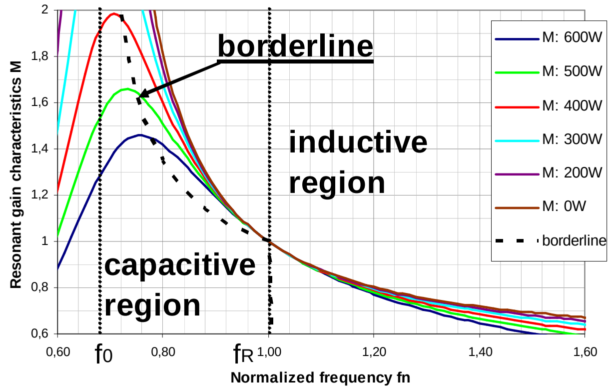


Fig. 4. Voltage gain curves of the resonant tank.

The voltage gain curves are calculated using (3), where Q is the quality factor (4), λ is the inductance ratio (6) and $f_N$ is the normalized frequency (7).

The $Z_0$ is the characteristic impedance (5) and n in (4) is the turn ratio of the transformer [2]-[6].

The operation of converter can be explained according to Fig. 5 in the next six intervals:

1. The resonant tank current from the previous interval is flowing now through the body diode of Q1. It causes that the voltage across Q1 drops to zero, and creates the zero voltage condition for the lossless turn-on of the switch.

2. Now the current flows through Q1, and has quasi sinusoidal character. Therefore the turn-off current is much smaller.

3. Q1 and Q2 are switched-off. The current of Q1 drops to zero immediately, but the voltage across the switch rises slowly due to

the charging of the output capacitance of the MOSFET. It reduces the turn-off losses.

4. Like in the first phase, the resonant tank current flows through the body diode but now of the switch Q2. The voltage of Q2 falls to zero. The switch is turned on at the zero voltage.

5. The current flows through Q2 similarly to the second phase.

6. The switches Q1 and Q2 are switched-off again. The current of Q2 falls to zero, but the voltage rises slowly again due to charging of the transistor output capacitance [7].

## III. Simulation

The resonant converter was simulated in the LTSpice IV program. Components of the resonant tank were calculated by equations presented in chapter II. Working frequency was set to 150 kHz. The collector current and collector-emitter voltage of the switch Q1 are shown in Fig. 6 (upper waveforms). It can be seen there that the switch Q1 starts to conduct when the voltage of the switch is zero and thus ZVS is achieved for the primary switches. When Q1 is turned-off, the current falls to zero, but voltages rise slowly, because the output capacitance of MOSFET is charging. On the bottom picture there are waveforms of the current and voltage of the rectifier diode D1. The current through the diode starts and stops flowing when the voltage is near to zero. Therefore the switching losses are minimal.

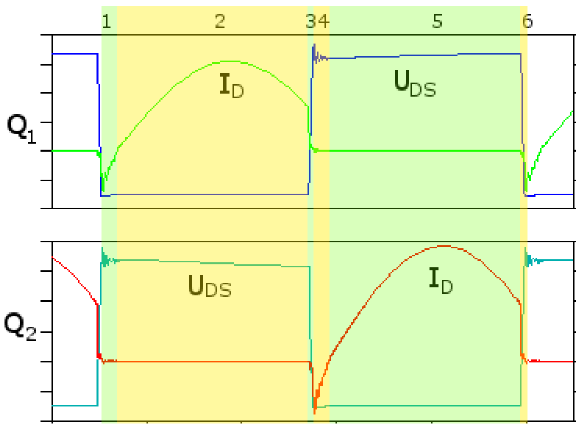


Fig. 5. Characteristic waveforms of collector – emitter voltage and collector current of half-bridge switches.

## IV. Laboratory Model of the Converter

The laboratory model of the resonant converter was built.

Parameters of the model:
Input voltage range $V_{IN}$ = 60-100 V.
Output voltage $V_{OUT}$ = 400 V.
Output power $P_{OUT}$ = 600 W.

Because the converter operates at a high switching frequency and in addition with high currents, each part of the converter circuit must be able to withstand this condition.

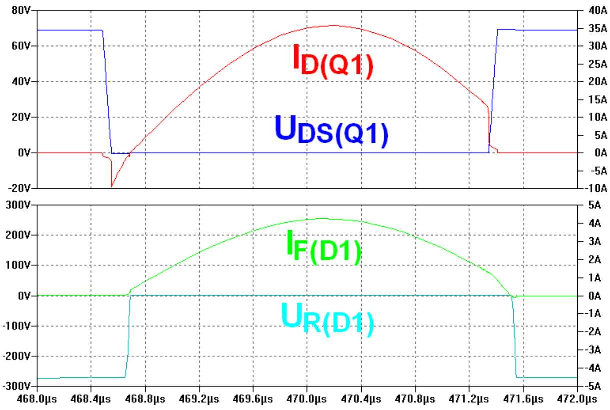


Fig. 6. Simulated waveforms of voltages and currents on switch Q1 and diode D1.

MOSFETs and rectifier diodes in the converter should have minimum loses in the conduction mode and short switching times. But there is no problem with the maximum rated voltage, because the voltage stress is very low due to the soft switching.

The input and resonant capacitors must handle very high load current at a high frequency. The quality capacitors of “KPI” type are suitable to fulfil these conditions.

The transformer can be designed so that it integrates the series and the parallel inductance in one circuit. In a classical transformer, the parallel inductance can by replaced by a magnetizing inductance, and series inductance by a primary leakage inductance. But there is problem with inductance ratio between leakage and magnetizing inductance, because the ratio is very small. One solution is to integrate an air gap into the magnetic circuit of the transformer. By adjusting the air gap it is possible to control the size of the magnetizing inductance and thereby also the inductance ratio (6). The litz-wire is used for winding to avoid skin effect [8].

## V. Experimental Results

The converter was connected to the DC voltage source, and loaded by an adjustable resistor. The input voltage was set to 90 V. Voltages and currents of primary MOSFETs and secondary rectifier diodes were measured by a digital oscilloscope. Results are in Fig. 7. Waveforms of the voltage and the current of the MOSFET Q1 are in the top picture and waveforms of the voltage and the current of the rectifier diode are below. We can see that the current starts to flow when voltage across MOSFET is zero and thus ZVS is achieved. Moreover, the switch-off current is minimal. The current through the rectifier diode starts to flow when the voltage is near to zero. It means a small switching loss. The voltage of the diode starts to rise when the current falls to zero. The ZCS of the diode is achieved, too. If we look at waveforms of both voltages, we do not see any overvoltage spikes. It means that there is no voltage stress across the MOSFETs and the rectifier diodes. Therefore we can use these components with lower break down voltage, and thus with better other parameters.

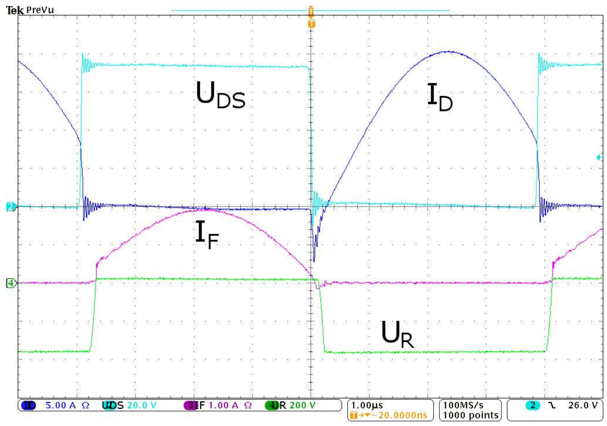


Fig. 7. Measured waveforms of currents and voltages on the primary MOSFET and the rectifier diode.

The efficiency of the converter was measured from 10% to 100 % of the rated load. Results are shown in in Fig. 8. As we can see; the efficiency is high in wide range of load, especially over 30 % load. In 50 % load the efficiency reaches its maximum, and up to 100 % load, slowly declines.

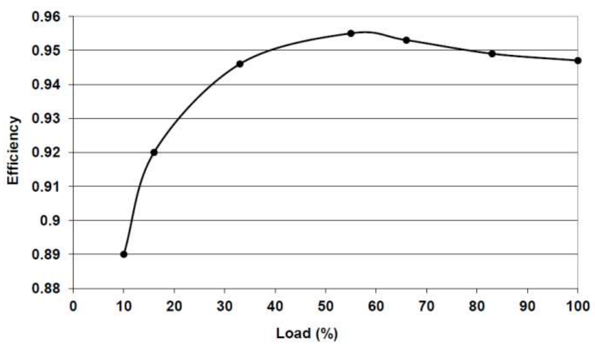


Fig. 8. Measured efficiency of the converter.

## VI. CONCLUSION

The resonant DC-DC converter with the LLC topology has many advantages compared to other converters. Due to the high efficiency over the entire operation range, the converter is well suitable for applications such as PV systems.

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