Model and Research of Power Electronics Solar Converter Working with Power Grid

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***Streszczenie*—In this paper a single phase grid-connected photovoltaic converter with maximum power point tracking algorithm is presented. This system is characterized by high efficiency and good output quality parameters of electrical energy. The implemented output inverter operates in current tracking controller mode. The output current (current of grid) is almost sinusoidal and the reactive power is equal to zero. Particular attention was paid to the MPPT algorithm. Its task is to ensure that the operating point PV cells to follow the maximum power point, depending on system conditions. Also, some results of simulation and experimental research of elaborated solar system was presented.**

I. Introduction

This article presents high voltage power and control structures of developed power electronic converter acting as a coupling between the AC power grid and renewable energy source (RES). In the presented case, this source is a group of photovoltaic (PV) panels. There implemented algorithm of MPPT (Maximum Power Point Tracking), which allows to achieve the maximum efficiency of the entire system was described.

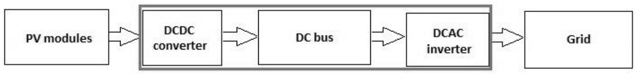
Furthermore, in order to provide high-quality energy parameters delivered into the grid, a transistor inverter with a sinusoidal output current was applied, which also allows the stabilization of the voltage on the system's DC bus. The article presents also built on earlier studies simulation model of described converter with regard to the way of emulation photovoltaic cell's duty cycle, which allowed a preliminary assess-ment of the correct functioning of the implemented MPPT algorithm.

II. Block Diagram and General Idea of Operation of Solar Energy Conversion System

The block diagram of elaborated system which allows transmission (and conversion) of energy from group of photovoltaic panels to alternating current power grid is presented in Fig.1.

We can distinguish in this case, the following blocks, namely:

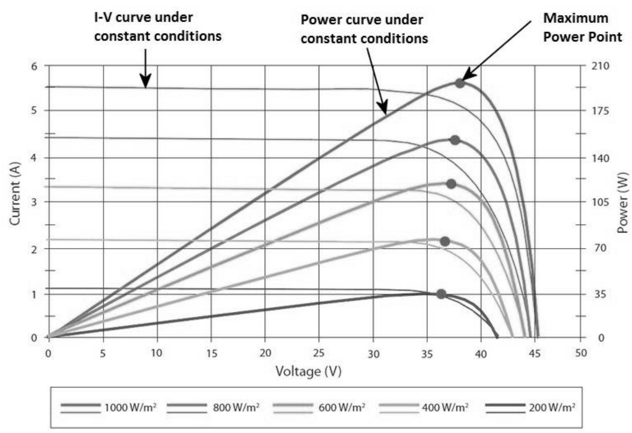
- group of PV photovoltaic panels,
- AC power grid,
- blocks of power electronic transducers acting as a coupling DC/AC, which includes: DC/DC BOOST converter, DC bus circuit, block of the DC/AC grid converter (grid inverter).



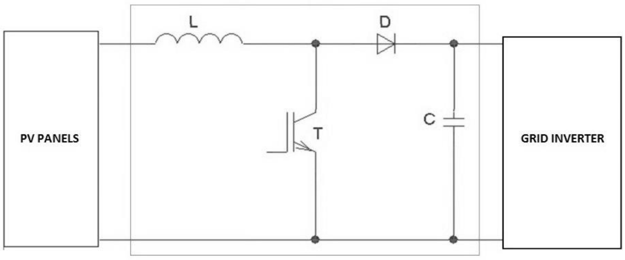
Rysunek 1. Block diagram of conversion and transmission system of solar energy.

In the presented case the use of group of photovoltaic panels with a band range of variation of the output voltage (dependent on the temperature, the level of load and intensity of incident sunlight) from 150 to 450V panels were assumed . An example of a family of current-voltage characteristics of photovoltaic PV assembly are shown in Fig.2 [1].

As one follows the power from the solar cell depends largely on mode of the load. Consequently, there exists the level voltage and current, for which the power obtained from renewable energy sources is the maximum (ie. The maximum power point - Fig.2). For this reason, in order to ensure optimal conditions of operation of the entire system, in the control system DC/DC converter MPPT algorithm was implemented. Its task is to ensure that the operating point of the cell follows the maximum power point, depending on the actual system conditions (eg. ambient temperature, intensity of the incident sunlight). Developed and implemented MPPT algorithm [2], [3] was presented in subsequent part of this article.



Rysunek 2. Family of current-voltage characteristics of photovoltaic group [1].



Rysunek 3. Schematic diagram of the DC/DC BOOST converter.

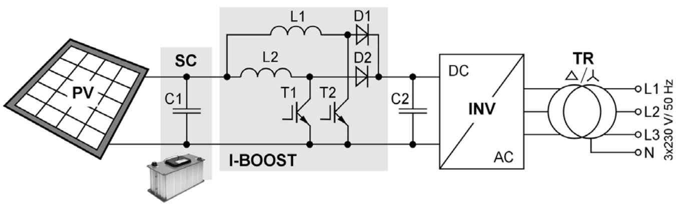
III. DC/DC Direct Current Circuit of Solar System

A. The Structure of Power Circuit

Because of the accepted range of output voltages of PV photovoltaic cells (150V-450V) and the required minimum value of the DC bus voltage, which should be in this case greater than the amplitude of the grid's voltage, high voltage power part of DC/DC converter is based on a system of pulse-type BOOST (Fig.3).

The purpose of this converter is to increase the output voltage of the photovoltaic panel group and to deliver energy to the capacitors included in the DC bus circuit. In Fig.3 a so-called bypass diode implemented in target circuit is omitted. This diode enables the transfer of energy from the PV cells to the grid inverter's input capacitors without BOOST type system. This situation is, however, possible only when the instantaneous value of the output PV cells' voltage is higher than the required voltage on grid inverter's input capacitors (the capacitors of inverter with sinusoidal current network).

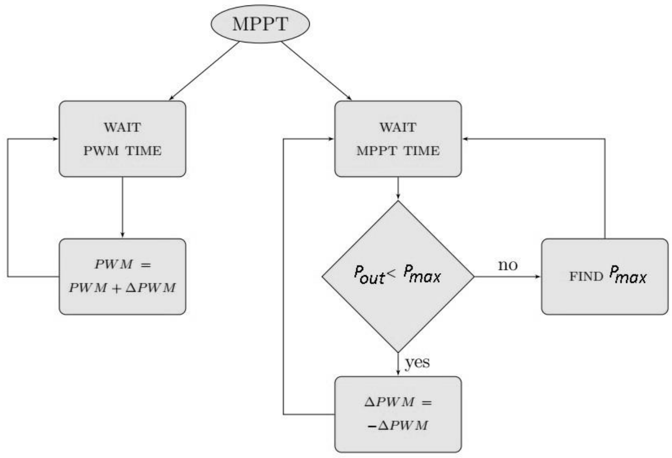
In case for large power the boost in interleaved mode (I-boost) may be implemented Fig.4. In this case the switching freqency of transistors can be reduced. In results the power loses of switching will be smaller. Additionaly the supercapacitors (SC) in DC circuit may be implemented. In this way we have additional energy buffor, which is very usefull during output voltage of PV cells fluctuations.



Rysunek 4. Boost converter in interleaved mode

B. Algorithm of Controlling Solar System's BOOST Converter - MPPT Algorithm

The purpose of the DC/DC Boost converter is to increase input voltage and supplying (recharging) capacitor group which is DC bus circuit, from which is powered a grid rectifier (inverter). In order to achieve the highest possible efficiency of use of PV photovoltaic panels' energy resources, the MPPT algorithm was developed and then implemented in the control system of BOOST converter [2], [3]. The block diagram was presented in Fig.5.



Rysunek 5. The block diagram of developed MPPT algorithm (Maximum Power Point Tracking)

In the developed algorithm the two main loops were separated. The first loop is responsible for modifying the duty ratio (PWM), which activates a key (T) of BOOST converter power section (Fig.3). This process takes place at certain marked intervals (PWM TIME) and it depends on the second loop, which determines the direction of changes in the duty ratio by a constant value defined as (ΔPWM). The task of the second algorithm's loop is to search for the maximum power that can be achieved at a certain working point of the system. Depending on the result of comparing the output power (P_{out}) for the current operating point of PV cells with a predetermined maximum value, the control system determines the direction of changes in duty cycle and looks for a new maximum power. This comparison is performed with a period defined as (MPPT TIME).

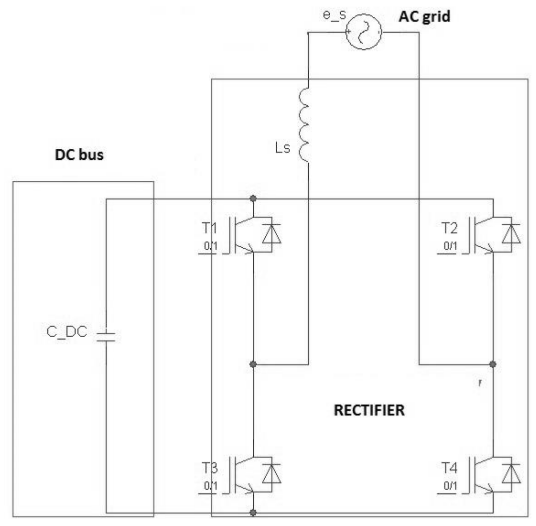
It should be noted that the task of DC/DC converter's control system is not to stabilize voltage in the DC bus circuit. This is a task of the regulator, which has been implemented in the control system of grid converter (inverter).

IV. The Structure and Algorithm of Control the Grid Inverter

A. Grid Inverter Circuit

Grid inverter (transistor rectifier operating in inverter mode) - directly responsible for the transfer of energy to the grid - is based on a transistor H bridge with inductive output filter. Schematic diagram of the system is presented in Fig.6.

The system transfers energy from the capacitor battery of DC bus circuit (rechargeable via the BOOST inverter) to the grid, while simultaneously ensuring as possible close to a sinusoidal signal grid current and the lack of reactive power generation. It should be noted that the correct operation of this

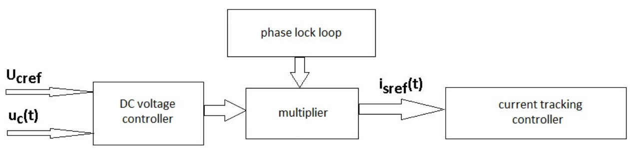


Rysunek 6. Schematic diagram of grid inverter.

circuit is possible only if the value of the instantaneous voltage in DC bus circuit is greater than the amplitude of the grid voltage. Basing on the definition of the active current [4] the grid inverter's control circuit operating in the current tracking controller was developed, enabling to adjust and stabilize the voltage on the capacitors of the DC bus circuit [5]. It should be noted that this function does not comply-in the described case a control system of the BOOST converter. It realizes only the MPPT algorithm.

B. Control Algorithm of Grid Inverter

Stabilization of the DC bus voltage is necessary for proper operation of the system. In the case of her lack voltage that varies in an uncontrolled manner - depending for example on the energy supplied from PV cells through the BOOST system. In the presented solution this function is performed by changing the amplitude of the grid rectifier's preset current [5]. As a result, it is possible to adjust the amount of power (active power) delivered onto the grid, and consequently to stabilize the voltage in the DC bus circuit. Block diagram, that shows the concept of operation of control system of the grid inverter, is presented in Fig.7.



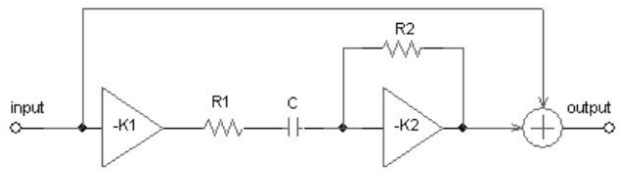
Rysunek 7. Block diagram of grid inverter's control system.

A block in the form of a DC voltage regulator is responsible for determining the am-plitude of the reference grid current $i_{sref}(t)$. The synchronization system of reference signal with the grid voltage signal is based on generator, which is generating sinusoidal signal with phase shift equal to 180 electrical degrees and a unit amplitude. In this way the reactive power was reduced theoretically to zero. The purpose of the next block in the form of a tracking controller of electricity supply is to provide grid current generation with a shape as close as possible to the reference signal $i_{sref}(t)$.

C. Structure of Current Regulator Used in Inverter's Control System

To assure correct work of presented grid inverter in block named current tracking controller (Fig.7) the unconventional structure of current regulator based on IIR filters was implemented. The filters utilized in control circuit must fulfill particular conditions. The three following criteria of filter structures and parameters selection were elaborated [5], [6]. The first of analyzed criteria, was the limitation of slew rate value of PWM modulator input signal. Fulfillment of this condition is necessary to assure the correct switching frequency, which must be equal to frequency of carrying signal.

The second criterion depends on assurance of the largest gain value of open-circuit transmittance in useful bandwidth, as well as the smallest value of this gain in bandwidth, where the shift phase is close to –180 el. deg.



Rysunek 8. The simulation model of additional high-pass filter (current regulator).

The last criterion, which has been analyzed during the researches, is the limitation of output signal spectrum due to aliasing effects risk. This limitation is obtained thanks low-pass filter implementation in control system and passive serial inductive filter at the output of inverter. During the simulation and experimental researches, several parameters of low-pass filter were analyzed. Also different additional structures of filters were elaborated. One of these has been filter about structure like in Fig.8.

This block is based on differentiator [5], [6]. The transfer function of presented regulator can be expressed by the following formula:

$$F(s) = \left(1 + \frac{K_1 s R_2 C}{1 + s R_1 C}\right) \frac{K_F}{1 + s T_{FDP}}. \quad (1)$$

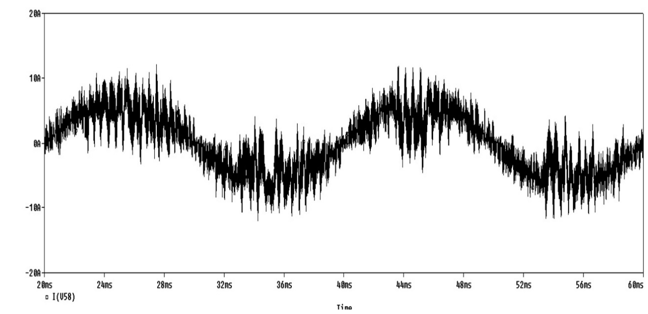
With help of this additional structure, minimization of delay effect in power electronics inverter with PWM modulator has been achieved. Thus, we can increase the resultant gain value of open-circuit transfer function, while the closed feedback loop circuit is still stable. In this way we can improve the quality of output signal of inverter.

V. Selected Results of Simulation and Experimental Research

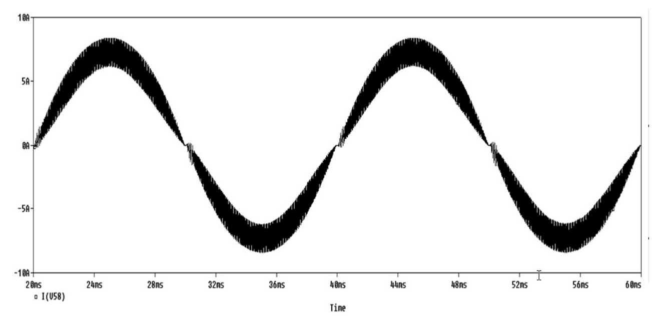
Preliminary simulations and experimental studies were performed for single-phase version of the system. Simulation model was designed using Cadence's Orcad suite. Basing on the results of simulation the correct functioning of proposed solution of converter's high voltage power circuit and control system was confirmed. An example of phase current signal of the grid (result obtained from the simulation) which characterizes low contents of higher harmonics (THD ratio equals 1,2 %) is presented in Fig.10. In grid inverter's control loop algorithm of unipolar modulation was used (pulse frequency was chosen at level of 12 kHz).

In Fig.9 the grid current for case, when the leakage current in circuit is present, was shown. This phenomenon is caused by the presence of the parasitic capacitance between the surface of photovoltaic panels and the surface of the earth. This is a very important issue. It contributes to a distortion of the grid current. Additionally, it causes also danger for human life.

One of the ways to eliminate this phenomenon depends on use a energetic transformer between power electronics inverter and the grid. This method was used in presented solution of solar inverter (Fig.10).

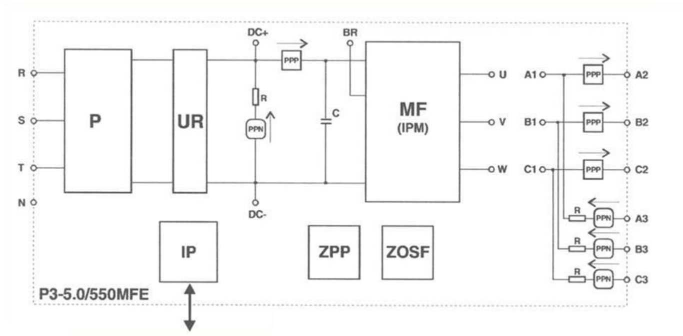


Rysunek 9. Grid current trajectory generated by the inverter with common-mode leakage current



Rysunek 10. Grid current trajectory generated by the inverter without common-mode leakage current

Experimental studies of the single-phase version was performed by using for e.g. converter type LABINVERTER P3-5.0 / 550MFE [7] and DSP development kit ALS-G3-1369 [8] equipped with a floating point digital signal processor Analog Devices SHARC ADSP-21369 [9], as well as laboratory DC power supply with adjustable current limit and output voltage (emulating the work of photovoltaic cells). The block scheme of LABINVERTER is shown in Fig.11.

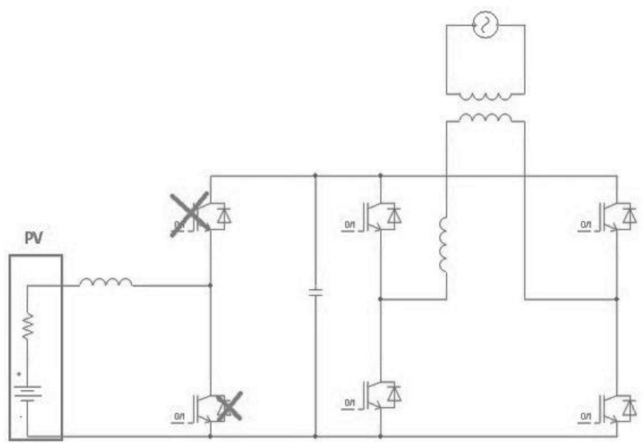


Rysunek 11. The block scheme of LABINVERTER [7]

The functions of each block of this power electronics converter are as follows:

- block (P) represents input diode rectifier (not used in described application),
- block (UR) is used to charging the capacitors implemented in DC circuit, when converter is started (not used in presented application),
- (MF) means 3-phase IGBT bridge (with help of this block the power circuits of the BOOST converter and also the output grid inverter were built),
- blocks (PPP) and (PPN) represent the current and voltage measure sensors.

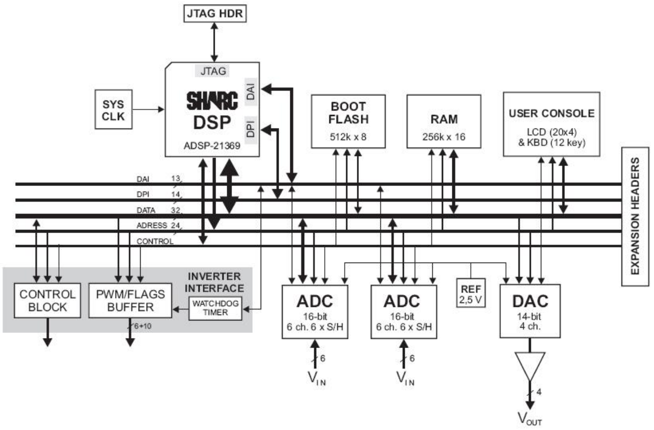
The way of connection in MF module, which was used in presented application of solar converter is presented in Fig.12. The upper transistor and the lower diode are not used in this case.



Rysunek 12. The way of connection used in MF module of LABINVERTER

The block scheme of ALS-G3-1369 digital system, which was used in aim of building control circuit, is presented in Fig.13. It is based on the floating digital signal processor

SHARC ADSP-21369, which is equipped with hardware co-processor of PWM (pulse width modulation) [9].



Rysunek 13. The block scheme of ALS-G3-1369 digital control system [8]

In the initial stage of research the laboratory DC power supply with adjustable current limit and output voltage, to emulate the work of photovoltaic cells, was implemented. Due to high dynamics of power supplies power reduction system, part of the research was carried with system switched off, which was replaced by connected in series resistor with output of the supply. As a result it was possible to verify correct operation of MPPT algorithm - checking the condition of matched output power value of the system to the maximum power generated by cell. In the final phase of laboratory tests the power supply was replaced by real photovoltaic cells. Below an example of experimental results were presented:

- the average value of the output voltage of photovoltaic panels: 233V,
- RMS voltage: 230V,
- the value of active power delivered onto the network: 940W,
- determined (maximum) system efficiency of 96% ,
- experimental studies have confirmed proper operation of the system and allowed the time constant tuning of the MPPT algorithm,

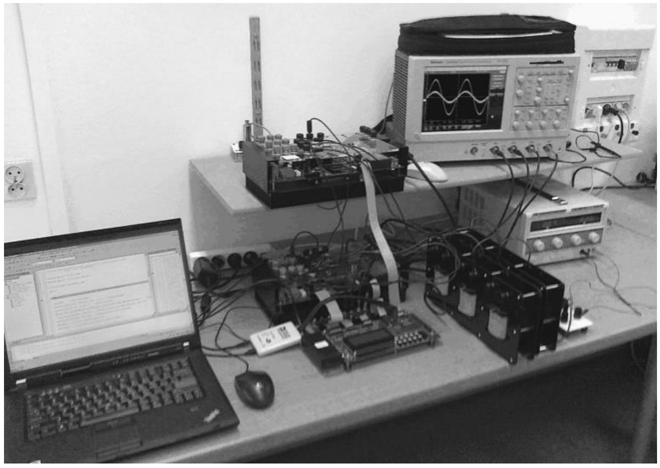
The laboratory system of described power electronics solar converter is shown in Fig.14.

Experimental studies have confirmed proper operation of the system and allowed the time constant tuning of the MPPT algorithm. It should be noted that for the proper functioning of this algorithm, the frequency of the loop responsible for changing the duty ratio should be greater than the frequency of the loop deciding on the direction of changes, which activates a pulse duty factor.

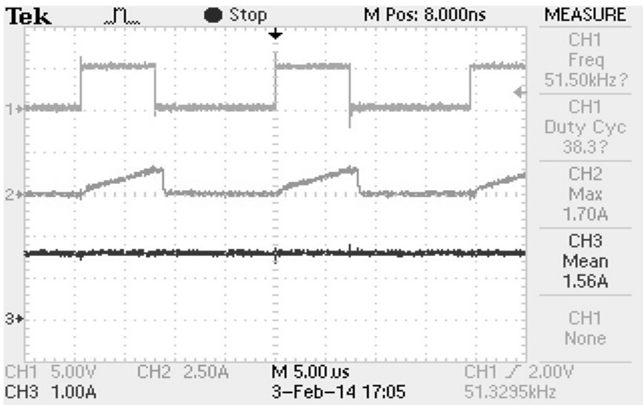
The chosen results of experimental research for boost converter and grid inverter are shown in Fig.15, Fig.16 and Fig.17.

VI. Conclusion

In the study DC/AC coupler of group of photovoltaic PV cells and industrial energy grid the simulation and experimental models of control system and high voltage power circuit



Rysunek 14. The laboratory system of solar converter with DC power supply emulating photovoltaic cells



Rysunek 15. Bost converter in discontinuous conduction mode. Waveform 1 - pwm signal, waveform 2 - transistor current in boost converter, waveform 3 - boost output current

were developed. The results confirmed the correctness of the theoretical assumptions, which in turn allowed to be compatible with the overall system. During the subsequent stages of research the modification, allowing for e.g. improvement of efficiency ratio - especially when system works with lower power than established- is foreseen. It is also foreseen the work upon the optimization of the MPPT algorithm for increased accuracy and the speed of following the disposal output PV cells power. Furthermore, the researches of for e.g. elimination or limitation of undesirable flow of current caused by parasitic capacitance between the surface of the cells and ground are developed.

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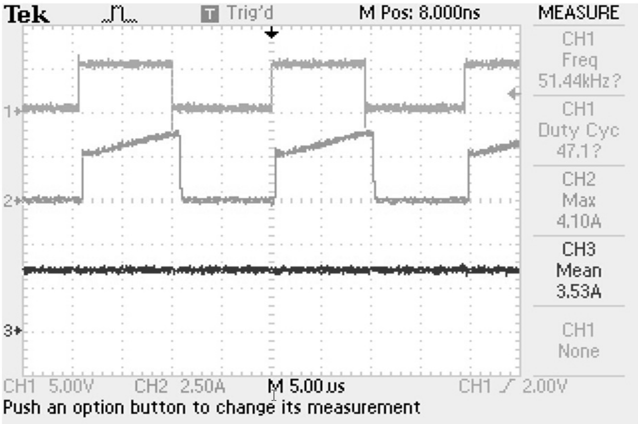
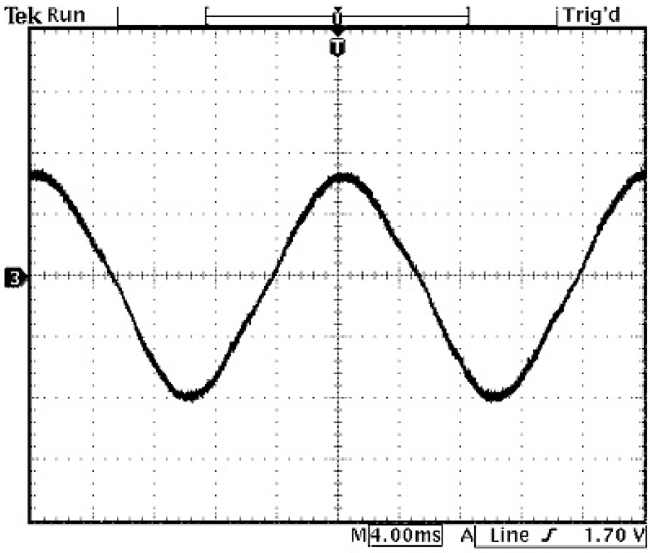


Rysunek 16. Bost converter in continuous conduction mode. Waveform 1 - pwm signal, waveform 2 - transistor current in boost converter, waveform 3 - boost output current



Rysunek 17. Experimental results - grid current trajectory generated by the inverter

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