RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
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RESEARCH AND DEVELOPMENT OF MODULAR UNINTERRUPTIBLE POWER SUPPLY SYSTEM WITH VARIED ENERGY SOURCES AND STORAGES

Doctoral thesis abstract

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Riga 2011

UDK 621.311.6(043.2)
St 354 r

Stepanovs A. Research and development of modular uninterruptible power supply system with varied energy sources and storages.
Summary of doctoral thesis.-R.:RTU, 2011.
37pp.

Printed according to the decision of IEE institute from April 4th, 2011. Protocol Nr.54.

This work is performed in the framework of Project "Support of development of the RTU doctorate" of the National Program "Support of development of the doctorate and postdoctorate researches", supported by the European Social Fund.

ISBN 978-9934-10-172-4

DOCTORAL THESIS
PRESENTED TO OBTAIN THE DOCTOR’S DEGREE IN ENGINEERING SCIENCES

Doctoral thesis for the doctor’s degree in the engineering sciences is publicly presented on the 6th of July 2011 in Riga Technical University, Kronvalda blvd. 1-117.

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CONFIRMATION

Hereby I confirm that I have worked out the presented thesis, which is submitted for consideration to the Riga’s Technical University for the degree of Doctor of engineering sciences. Doctoral thesis has not been submitted in any other university for obtaining the Doctor’s degree.

Andrejs Stepanovs …………………………….

Date: ………………………

The doctoral thesis is written in English language, contains: 190 pages, introduction, 5 chapters, conclusions, 190 figures, 72 formulas, 29 tables, 68 references and 4 appendixes.

SIGNIFICANCE OF THE TOPIC

Alternative energy sources nowadays are becoming more and more popular. There are many examples when the alternative power sources are integrated into electrical grid of buildings.

The markets offer different uninterruptible power supplies systems solutions that do not use heavy, bulky, environment unfriendly, and low-reliable lead-acid batteries, but instead of that they utilize such energy storages like supercapacitors or flywheels.

Future “green” uninterruptible power supply systems will utilize alternative energy sources and the alternating energy storages. To combine all these together it is necessary many different converts. It makes the system quite complicated. Due to this many different ways of unification are offered .

In this doctoral thesis versatile power modules (VPMs) that unify and simplify the uninterruptible power supply assembly are offered . Novelty and difference from many existent modules of UPS is multifunctionality of VPM. Existent modules allow only to increase power or to add module for system redundancy for higher reliability. The VPM module allows to connect alternative energy sources and storages like supercapacitor, flywheels, fuel-cells, photovoltaic panel, wind-turbines and etc. At the given moment on the market there are many different types of UPS systems. Some of them are not expandable at all. Some of them can be parallel for higher power and reliability increasing. Some of them utilize alternative storage like supercapacitors and flywheels. Most advanced UPS systems even switch between operation modes (double conversion mode or line-interactive mode) for higher efficiency or higher protection (more details can be found in first chapter).

The modular UPS systems that are researched in the thesis combine most features of the UPS systems mentioned above.

It allows:

- To build converters like n-phase invertors, n-phase active rectifiers, DC/DC converters
- To build different UPS topologies like “standby UPS”, “on-line UPS”, “DC-UPS”
- To utilize different energy storages like supercapacitor, flywheels
- To utilize different energy sources like photovoltaic panels, wind-turbines, fuel-cells
- To build UPS systems for remote places with alternative primary energy source where power grid is not available

The power converters that are built on VPM can be easily rebuild to any another system.

Utilization of alternative energy sources will reduce CO_2 emission, but utilization of alternative storages can increase system reliability as well as the alternative storages.

OBJECTIVE OF THE WORK AND FULFILLED TASKS

The main goal of the thesis is to develop uninterruptible power supply system that can utilize different energy sources (electric grid, diesel-generator, photovoltaic panel, wind generator, fuel cell) and different energy storages (rechargeable batteries, supercapacitor, flywheel).

To realize the stated aim it was decided not to develop different converters for each energy storage or source, but to develop versatile power module that can work like the necessary converters. To do that it was necessary:

- to analyze converter types that are used with defined energy sources or storages and to choose power circuit for versatile power module
- to develop modular power board
- to develop driver circuits
- to develop measurement circuits
- to develop effective and modular cooling system

METHODS AND MEANS OF RESEARCH

There were developed precise Matlab-simulink models of versatile power modules and other elements of UPSS. It simplifies debugging of different power circuits and control algorithms. So, all the circuits before experimental testing were simulated and only after successful simulation results the experimental test were made. Simulated data and experimental data were compared and analyzed.

SCIENTIFIC NOVELTY

- The uninterruptible power supply system that can utilize different energy sources and storages is developed .
- The versatile power module for easier and faster assembling of different uninterruptible power supply systems is developed
- Few VPMs can be stacked together not only for interfacing with different energy storages and sources, but also for UPS power increasing.

PRACTICAL APPLICATION OF THE WORK

The developed uninterruptible power supply system (UPSS) can utilize such energy sources as electric grid, diesel-generator, photovoltaic panel, wind generator, fuel cell as well it can store energy in rechargeable batteries, supercapacitors, flywheels.
It allows to get many different combinations of UPSS. Due to that UPSS for any case can be selected:

- one-phase or three-phase classical UPPS topology
- it is possible to assemble UPS with different combinations of n-phase input and n-phase output
- UPSS for remote places where isn't accessible electrical grid and as primary energy source can be used photovoltaic cells or wing generator
- It can be assembled UPSS which store energy in supercapacitor or flywheel instead of lead-acid batteries. The supercapacitor and flywheels have advantages over batteries in UPSS with diesel-generator
- Can be assembled DC-UPSS that have higher efficiency than AC UPSS

Such UPSS can help to reduce CO emissions and to do UPSS more environmentally friendly.

As well the VPM can be used in laboratories form fast prototyping of different converters like inverters, active rectifiers, active front-end converters, step-up or step-down converters, frequency converters and even active filters.

Designed modular, cheap, easy in making primary heat sink construction can be easily updated for another powers and shapes and implemented in many different future projects where liquid cooling is necessary.

The developed precise Matlab-simulink model of the photovoltaic panel that is installed on the roof of the "Institute of Industrial Electronics and Electrical Engineering" also can be used in future project for other systems simulation approbation.

WORK APROBATION

The approbation of work has been realized participating the following international conferences:

1. The 10th International Biennial Baltic Electronics Conference, BEC2006, Estonia, Tallinn, 4.-6. October, 2006
2. Power electronics and energy efficiency 2006, Ukraine, Alushta, 17.-21. September, 2006
3. 4th International Symposium – “Topical Problems of Education in the Field of Electrical and Power Engineering”, Estonia, Kuressare, 15.–20. January, 2007
4. 12th European Conference on Power Electronics and Applications, Denmark, Aalborg, 2.-5. September 2007.
5. Power electronics and energy efficiency 2007. Ukraine, Alushta, 18.-22. September, 2007.
6. 5th International Symposium – “Topical Problems in the Field of Electrical and Power Engineering”, Estonia, Kuressare, 14.–19. January, 2008.
7. Power electronics and energy efficiency 2008. Ukraine, Alushta, 17.-21. September, 2008
8. The 11th International Biennial Baltic Electronics Conference, BEC2008, Estonia, Tallinn 6.-8. October, 2008.
9. 50th International Scientific Conference, Latvia, Riga, 11.–13. October, 2009
10. Power electronics and energy efficiency 2009, Ukraine, Alushta, 21.-26. September, 2009.
11. 8th International Symposium – “Topical Problems in the Field of Electrical and Power Engineering”, Estonia, Parnu, January 11-16, 2010
12. The 51st International Scientific Conference „Power And Electrical Engineering”, October 2010, Riga, Latvia.
13. 14th International Power Electronics and Motion Control Conference (EPE-PEMC2010), Macedonia, Ohrid, 2010
14. Power electronics and energy efficiency 2010, Ukraine, Alushta, 20.-25. September, 2010.

AUTHOR’S PUBLICATIONS

1. * Galkin I., Stepanov A., Laugis J. Outlook of usage of supercapacitors in uninterruptible power supplies. The 10th International Biennal Baltic Electronics Conference, 2006, 4.-6. October, Estonia, Tallinn
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18. * Stepanov A., Galkin I., Gook A. Development of versatile modular power converter for educational and research needs, 14th International Power Electronics and Motion Control Conference (EPE/PEMC 2010), 6.-8. September 2010, Ohrid, Republic of Macedonia.
19. * Galkin I., Stepanov A., Suskis P. Selection of power factor corrector for modular uninterruptable power supply system, 14th International Power Electronics and Motion Control Conference 2010, 6.-8. September 2010, Macedonia, Ohrid.
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* - articles have been published in the international database of the IEEE.

Contents of Doctoral Thesis

Introduction

The electric power in modern world is necessary everywhere. Without it cannot operate any manufacturing, hospitals, banks etc. Modern electrical equipments give many advantages to us, but this electrical equipment for correct operation need qualitative power supply. Good example is computer, which gives us endless opportunities: assistance in many jobs, help in studies, communications with the world, entertainment and etc. But many people also know disappointment and sorrow when due to grid fault they lose many hours of work. Best possibility to prevent grid outages it is to connect load through uninterruptible power supply (UPS). There are different topologies of UPS that give different class of protection and protect from different grid events. Each topology has advantages and disadvantages. To understand which type of protection needs load it is necessary to understand common grid faults and it danger.

Generally speaking there is no cost-effective and versatile solution for all types of loads (equipment) and each type of UPS better fits to defined loads and defined case. AC motors works better with pure sine-wave, but mostly pure sine-wave has on-line topologies and sometimes line-interactive UPS. Most equipment with switching mode power supplies (SMPS) can be supplied with any form of voltage: square, stepped square (quasi sine-wave), sine-wave and even DC voltage. That’s why for high efficiency and high reliability can be used UPS system with different topologies.

Another topical point is environmentally friendly devices with alternative energy sources like wind-turbines and photovoltaic panels that reduce CO emission. Nowadays on the market can be found many different solutions for solar and wind energy harvesting. But these systems cannot be easily integrated in UPS system. Only some manufactures offer quite flexible solutions that allows to assemble different systems and to manage harvested energy in many ways. Its solutions allow to assemble supply systems that:

- can operate as a stand alone systems;
- can recuperated harvested energy to the grid;
- system can operate as a backup system.

To realize these systems the manufacturers offer many types of inverters for each type of system:

- Inverter for grid-tied system
- Inverter for off-grid system
- Inverter for backup system

The inverters that are designed for backup systems have additional inputs and outputs for diesel-generator interfacing. In case of grid outage and lack of power generated by photovoltaic system it starts DG or use stored energy in batteries. Such system in future will become more and more popular. But most nowadays systems are designed to use lead-acid batteries as backup storage.

As it will be discussed in next chapters in some cases higher reliability can give alternative backup storages like supercapacitors and flywheels. In future will increase interest to the alternative energy storages due to its high reliability and environment friendly technology. It means that also will increase needs in UPS systems with these energy storages.

As can be seen there is need in many different converters that interconnect all above mentioned energy source and storages. But there is hard to find manufacturer that offer all these kinds of converters for UPS system.

That’s why it was decided to develop versatile power module which can be used to assemble different UPS systems or many another power converters.

1. Analysis of grid problems and methods of their solving

1.1. Classification of grid problems

Grid events are classified by standard EN 50160 [2]:

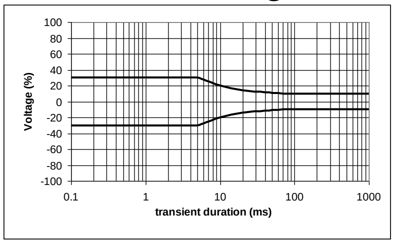
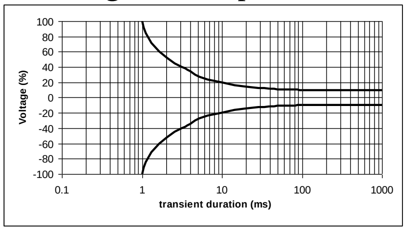
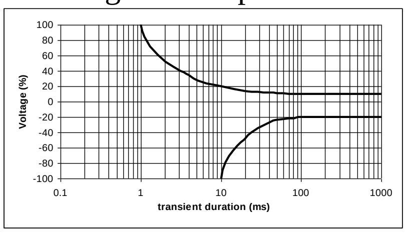
1) **Power frequency**
2) **Voltage magnitude variations**
3) **Rapid voltage changes**
4) **Supply voltage dips**
5) **Short interruptions of supply voltage**
6) **Long interruption of supply voltage**
7) **Temporary overrvoltages**
8) **Transient overvoltages**
9) **Supply voltage unbalance**
10) **Harmonic voltage**
11) **Interharmonic voltage**

In theory, all of these grid events (voltage deviation outside ±10% of rated voltage) can cause electrical equipment fault, especially in sensitive electronic equipment. Often overvoltages above +10% cause reduction of equipment lifetime, but high overvoltages can damage equipment. In switching mode power supplies (SMPS) undervoltages below −10% cause consumption of higher current from grid, but due to that, conductors, inductors and other elements can have temperature rise, that in longer time also can cause equipment damage. Large undervoltage can cause equipment immediate shutdown. Undervoltages take up large part (up to 95%) of grid faults and they are classified in a power quality category as voltage dips. Voltage dips are probably the most annoying of all power quality problems [1, 3, 4, 7]
It must be noted that voltage dips and short interruptions of supply voltage cause 2/3 of all damages (losses) [4].

1.2. Classification of UPSs

To protect load from grid problems it can be connected to grid though UPS. Classification of UPS by performance clarifies standard EN 620040-3 [3, 6]. Table 1.1. explain classification code.

Table 1.1. Explanation of classification code

X X X -	X X -	X X X
Output dependency	Output waveform	Output dynamic performance
VFD – voltage and frequency dependent To this group refers “Stand-by” UPS. Protects from: 1) Grid failure; 2) Voltage dips; 3) Voltage peak ________________ **VI – voltage independent** To this group refers “Line interactive” UPS. Protects from: 1) Mains failure; 2) Voltage dips; 3) Voltage peak; 4) Undervoltage; 5) Overvoltage ________________ **VFI – voltage and frequency independent** To this group refers “Online” UPS. Protects from: 1) Mains failure; 2) Voltage dip; 3) Voltage peak; 4) Undervoltage; 5)Overvoltage; 6) Surges; 7) Frequency variations; 8) Voltage distortions; 9) Voltage harmonics	S – sinusoidal voltage with THD<8%. All harmonics have to be in the range of standard EN 61000-2-2 X- generated waveform is sinusoidal with linear loads. With non-linear loads waveform THD will exceed 8% and can be in the stated range by manufacturer Y – Generated waveform is non-sinusoidal with THD that exceed the range of EN 61000-2-2.	1 – no break of voltage  2 –voltage break up to 1 ms  3 –voltage break up to 10 ms 

From all the above mentioned it can be concluded that best one protection is provided by means of UPS with classification code “VFI-SS-111”. This means that output voltage:

- Does not depends on input voltage
- output voltage in all operations mode (battery, grid, bypass) is sinusoidal
- output voltage has no interruption in the case of switching between modes
- in transient regimes output voltage changes do not exceed ±30% of rated voltage

There are also many another types of UPS, but they all will not be discussed. From all another types it will be noticed only “hybrid UPS” (also known as double conversion on demand) and DC-UPS [8, 9], because they having prospects in future due to high efficiency.

Table 1.2. Another types of UPSs

Hybrid or Double Conversion on Demand	VFI –Voltage and frequency independent (in online mode)	The same as on-line UPS	In normal operation mode operates as line-interactive with high efficiency, but in case of any input voltage deviation it is switched to “online” mode.
DC UPS	VFI –Voltage and frequency independent	The same as on-line UPS	Rectifier operates permanently.

1.3. Review of energy sources for uninterruptible power supply system and their interfacing converters

Main energy source of all uninterruptible power supplies in normal operation mode is power grid. When power grid is inaccessible UPS supply load from another energy source. They can be divided on two groups: AC sources and DC sources (table 1.3).

Table.1.3. Energy sources

AC sources	DC sources
Grid - power source with availability near 99.9% + relatively cheap energy source - need to be converter to store in energy storage **Diesel-generator** + highly reliable energy source + energy amount practically limited with fuel tank + can be used in remote places instead of grid - high price of generated electrical energy - in case of usage inside buildings have to be used specially designed room for noise and vibration reduce **Wind turbine** + environment friendly energy source + can be used in remote places instead of grid - non-constant power source - need power converter to interface with load **Flywheel*** + environment friendly energy source (energy storage) + high power density + high reliability + for short time (below to 30sec) backup can be cheaper power source that battery - low energy density (backup time below 30s) - need quit complex bidirectional DC/AC converter	**Battery** + cheap power source at longer backup time - low power density - need power converter to interface with AC load **Supercapacitor** + highly reliable energy source + many charge/discharge cycles - high price at longer backup times - need power converter to interface with AC load **Photovoltaic panel** + environment friendly energy source + can be used in remote places instead the power grid - non-constant energy source - Expensive energy source **Fuel-cell** + theoretically unlimited energy source (practically limited with hydrogen fuel tank) + environmentally friendly - very expensive energy source - need power converter to interface with AC load **Flywheel*** + environment friendly energy storage + high power density + high reliability + for short backup time (below to 30sec) can be cheaper power source that battery - low energy density (backup time below 30s) - need quit complex bidirectional DC/AC converter

*- flywheel operate with AC voltage, but some manufacturer has developed flywheels with integrated DC/AC converter. In this case flywheel behave like DC source.

1.4. Reasons for development of uninterruptible power supply system based on versatile power modules

As it was mentioned above there are many different energy sources that could be used in UPS systems. Each of them has disadvantages and advantages. Due to that UPS system never contain only one energy source. In this case each energy source completes another and systems become more reliable. In a system with not very high reliability usually only 2 energy sources are used (most common grid and lead-acid batteries are). In more reliable systems in most cases there are 3 energy sources (most common are: the grid, the lead-acid battery and the diesel-generator) [5].

Nowadays on the market there are many types of UPS systems with different combinations of energy sources like supercapacitors, flywheels, fuel-cells, photovoltaic panels and wind turbines [11,19,20,21,22]. But most of these systems even now are not extendable with another kind of energy source. For example, UPS systems which are designed to use lead-acid batteries, as a backup storage, can not be easily rebuilt for supercapacitor (or another storage) utilization. This means that for a system with many different energy sources many different converters are necessary. Many different types of converters complicate system and make it unstable.

Thus it was decided to develop versatile power module (VPM) that simplifies system assembly with any energy sources or storages.

Basically power converters (common configurations of converters like rectifier, inverter, step-down DC/DC, step-up DC/DC and etc) consists of one or few half-bridge legs (in series connected two transistors with free-wheeling diodes) that allow assembling almost any converter from n-number of VPM.

In the thesis "*VERSATILE POWER MODULE"* is proposed that has all necessary parts to operate like a simple power converter. Few interconnected power modules can operate like most of UPS topologies (also 3-phase topologies), frequency converter, active filter etc.

The proposed VPM must contain:

- two power switches with anti-parallel diodes that are connected as half-bridge leg
- Transistor's drivers
- DC –link capacitors
- Measurement elements
- Cooling system
- Auxiliary power supply
- Control device

The proposed circuit of modular power converter ia depicted in fig. 1.1.

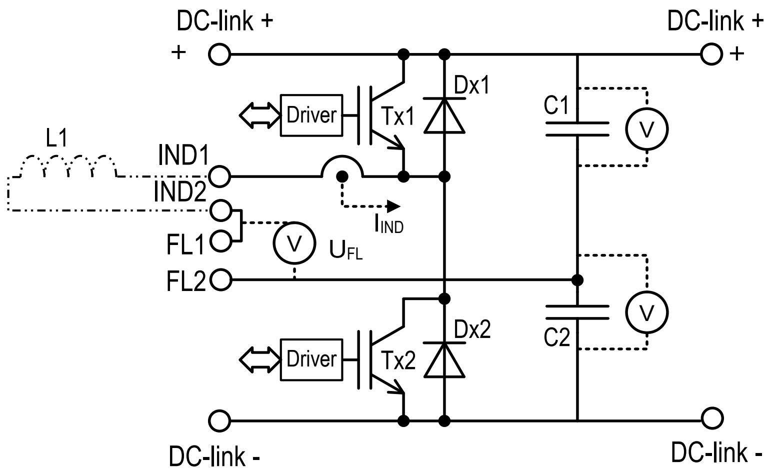


Fig. 1.1. Power circuit of versatile power module

Power converter assembled with VPMs gives the possibility to choose UPS topology, but this gives the possibility to make a choice between power quality or efficiency. Most of the UPS available on the market are designed to operate only in one mode and it can not operate in another mode (exception is "hybrid" UPS topology [9] that can operate as "line-interactive" UPS or "online" UPS).

2. Development of Versatile Power Module

In chapter 1.4. the necessity of versatile power module was discussed. In this chapter developed of the VPM is described.

2.1. Power board

It was decided to develop versatile power modules with rated current up to 20- 25A that gives inverter or rectifier power up to 4-5 kW.
During power board development it were applied approaches that minimized stray inductances of current conductors, minimize overvoltages on semiconductor switches during switching and increase reliability of power board. Fig.2.1. represents sketch-up of PCB, transistor and heat sink placing.

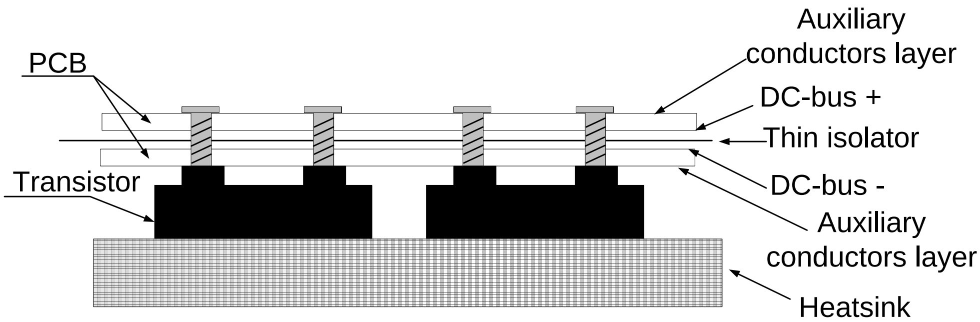


fig.2.1. Cross-section of power board of versatile power converter.

Assembled power board of versatile power converter is shown in fig.2.2.

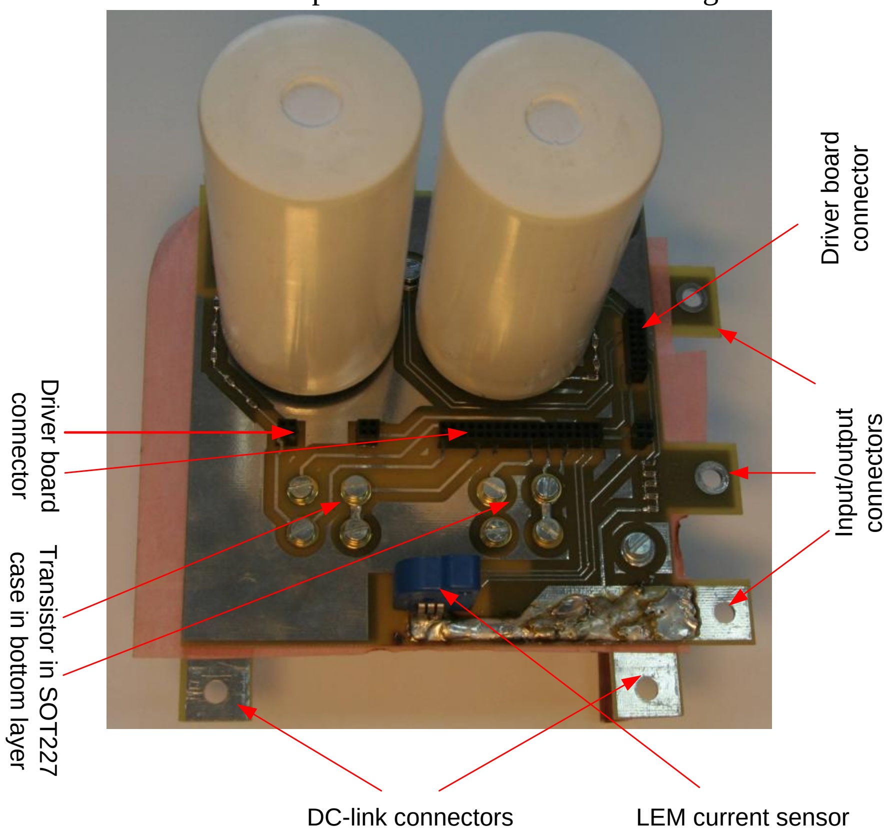


Fig.2.2. Versatile power converter without driver and measurement boards

Figure 2.3 demonstrates experiential data of switching of transistor and diode. Experiments were made with DC-bus voltage 550V and commutation current 25A. Testing with higher voltage (at 25A current) is not allowed by laboratory equipment.

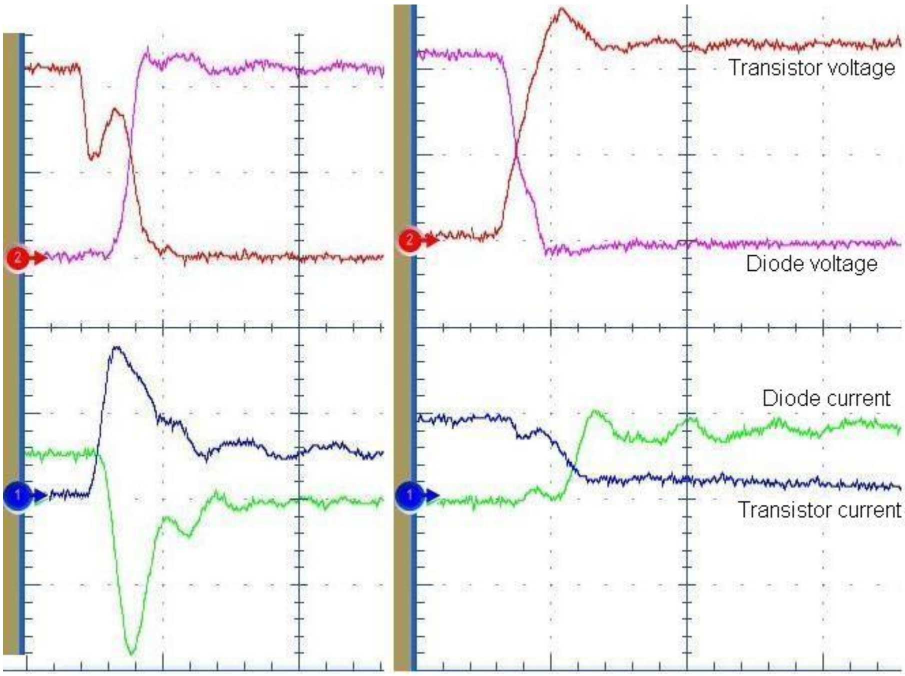


Fig. 2.3. Transistor and diode switching (time scale is 200ns per division, Voltage scale is 250V/div, current scale is 25A per division)

As can be seen during diode close overvoltage on transistor is relatively small (15-20% of rated voltage). Due to this 1200V transistors can be safely used with DC-link voltage up to 800V.

2.2. Driver board

Driver board has to ensure safe and reliable control interface and local protection from incorrect control signal.

To ensure mentioned demands the driver board (fig.2.4.) contains:

- Galvanic isolated power converter, that converter high DC-link voltage (800V) to 15V. The 15V are necessary to supply the transistor driver.
- 15V to 5V DC/DC power converter, that supplies opto-recivers, opto-transmiters, and logic elements
- Two channel transistor driver (Scale 2SD106A-17_E drivers manufactured by „CT Concept")
- Opto-recievers and opto-transmiters, that ensure galvanic (optical) isolation of control signals and transistor status signals
- Logic elements to ensure protection over simultaneous opening of transistors

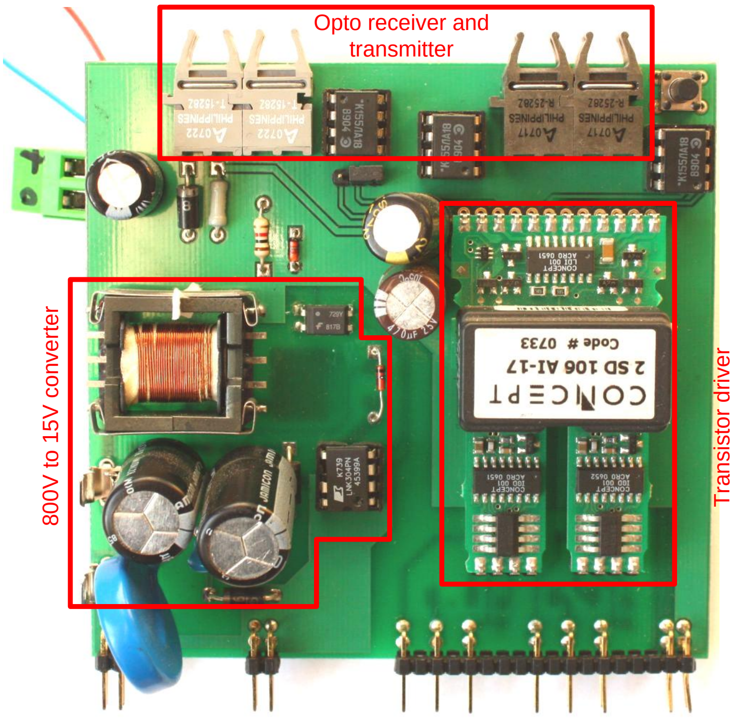
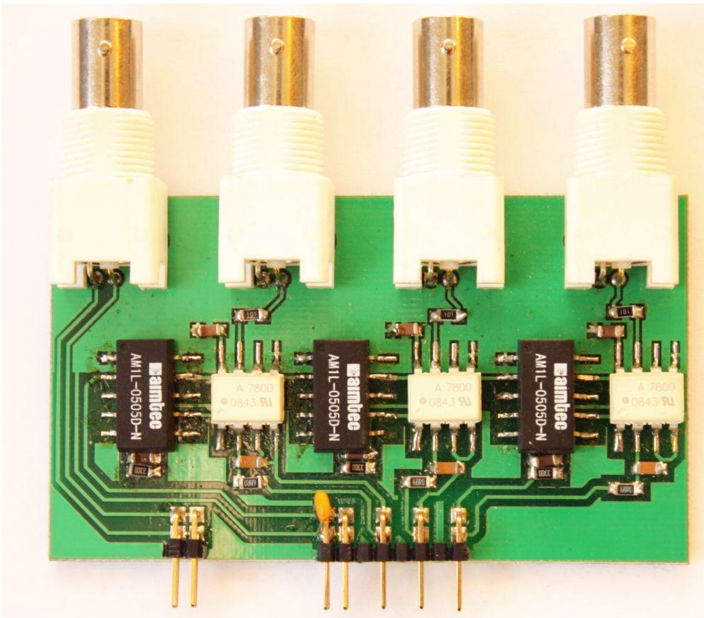


Fig.2.4. Photo of driver board

2.3. Measurement board

Measurement board (fig.2.5.) provides feedback for control system and galvanic isolation of measured signals. It has 3 channels with 3 BNC connectors that ensure both capacitors and input/output voltages measuring and one BNC for input/output current measuring.



b)

Fig.2.5. Photo of Measurement board

2.4. Adaptor board

In future the “Versatile power modules” will be controlled with DSP board, but for much faster development of control algorithms and its simple debugging it was decided to use real-time controller dSpace DS1103.
As a control device and measurement board can have different signal levels it is necessary additional elements to equalize levels of measured signals. The adaptor board (fig.2.6.) receives measured signals through BNC connectors, but voltages dividers with potentiometers allow adjust signal levels.

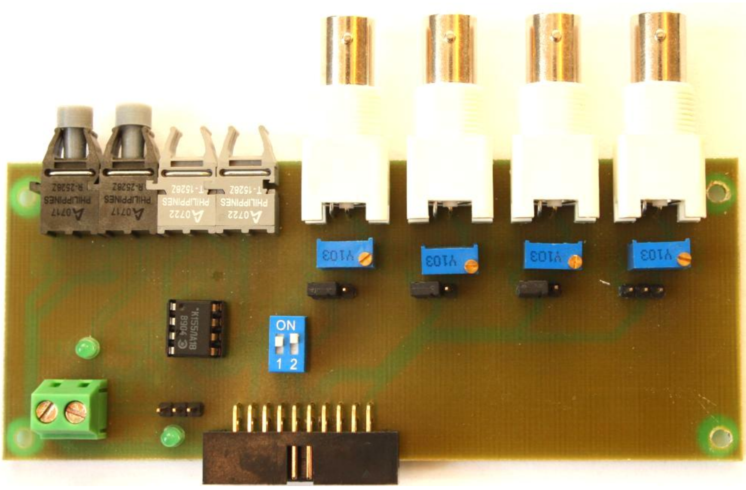


Fig.2.6. Adaptor board

2.5. Cooling system

Modular construction of power converter means also modular construction of heat sinks. To create compact and modular heat sink it was decided to develop water cooling system.
Water pump, secondary heat exchanger, tubes, coolers, etc were bought on the local markets. As it was mentioned above each module has 2 semiconductor devices connected into the phase leg. As there are two close placed switches, they can be put both on the same heat sink. As it is hard to find heat sink with specified sizes it was decided to develop primary heat sink
To find better heat sink construction it was designed, calculated [14,15,16,17] and tested 4 different primary heat sinks constructions. Best one construction with R_{th} – 0.019 C^0/W was chosen for further usage (fig.2.7).

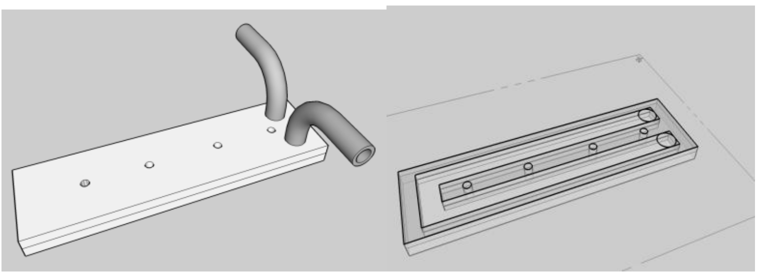


Fig. 2.7. Heat sinks constructions

3. Development of Matlab-simulink model of versatile power module its control core and elements of UPSS

Before the experiments it was decided to evaluate converters (inverters, rectifiers, step-up/step-down converters and etc) and its control algorithms using simulations in MATLAB-SIMULINK. The simulation was dome in Matlab-simulink, because it is compatible with real-time control device dSpace DS1103. The control algorithm from Matlab-simulink with small changes can be used for code compiling for dSpace.

3.1. Model of versatile power module

Matlab model was built by similar topology as a real versatile power converter. Due to this Matlab-simulink model contains the same main blocks plus one auxiliary block for voltages and currents analyzing (fig.3.1):

- Power board
- Measurement board
- Driver board
- Control board

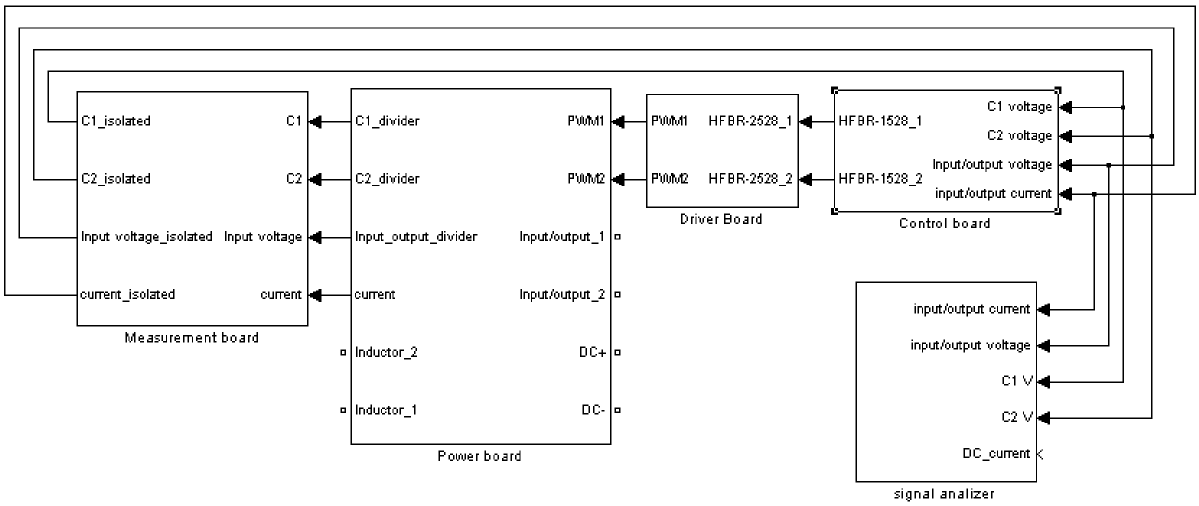


Fig. 3.1. Matlab simulink model of versatile modular power converter

3.1.1. Model of Power board

Power board subsystem (fig.3.2.) contains same elements as real power board converter with all possible parameter close to the real parts parameter.

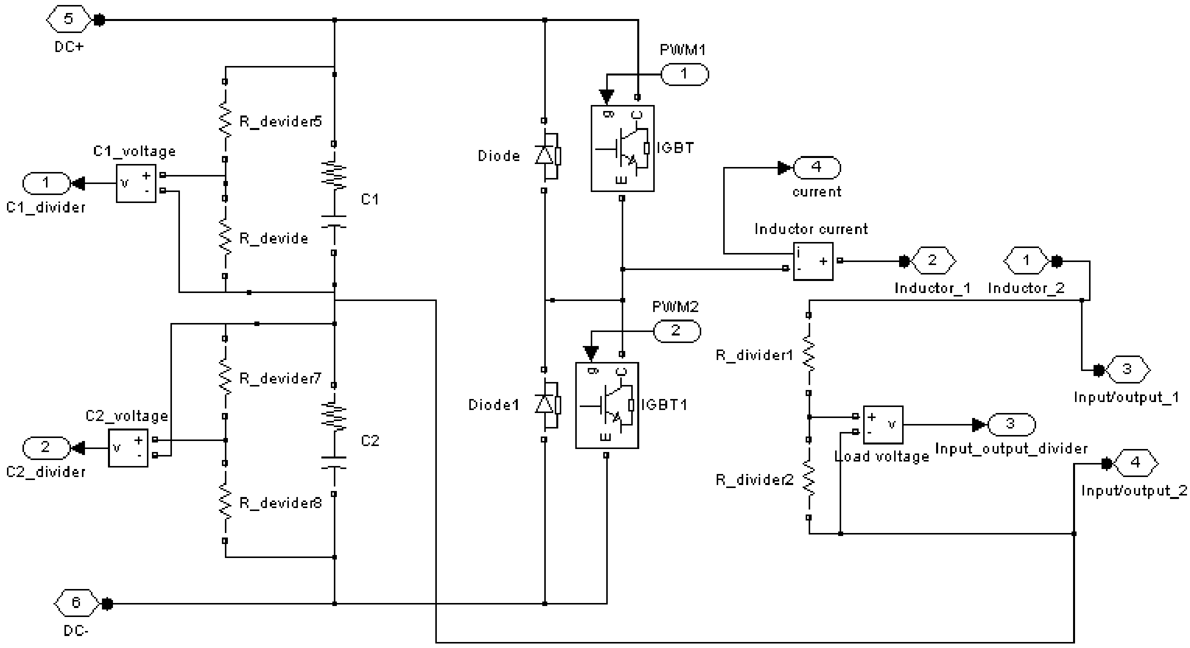


Fig.3.2. Power board subsystem circuit

3.1.2. Model of Measurement board

Figure 3.3. presents the subsystem of measurement board. One of the tasks of this subsystem is to take in to account bandwidth and time delay of HCPL7800 (fig.3.4.) and LEM LTS 15-NT (fig.3.5).

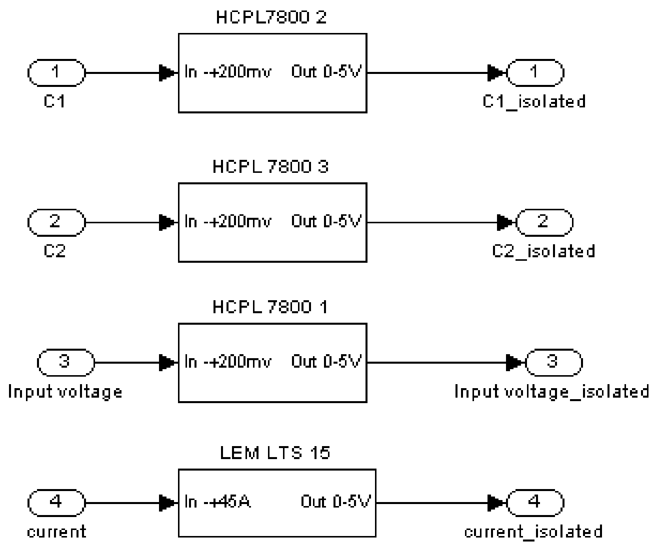


Fig.3.3 Measurement board subsystem

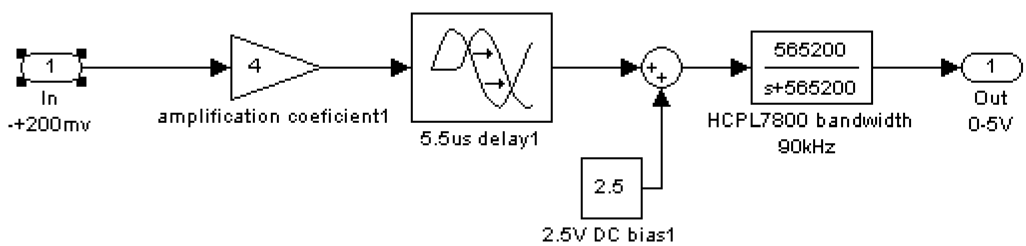


Fig.3.4. AVAGO HCPL7800 Matlab model that takes into account its amplification coefficient, bandwidth, phase shift and voltage bias.

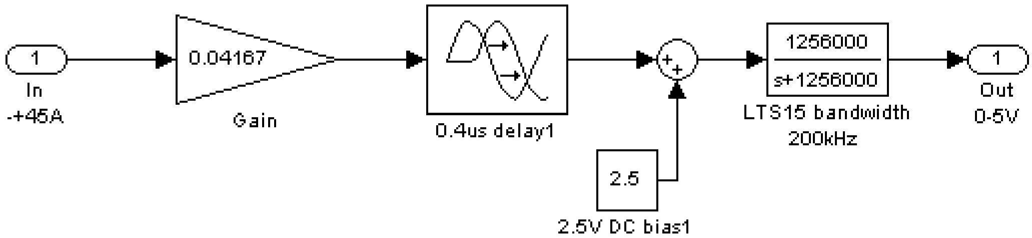


Fig.3.5 LEM LTS15 Matlab model that takes into account its amplification coefficient, bandwidth, phase shift and voltage bias.

3.1.3. Model of Driver board

Matlab-simulink model of driver board is given in figure 3.6. Main task of this subsystem it is to take into account control signal delay. In these blocks are included delays of all parts that are involved in control signal transmission (logic elements delays, opto-transmitter delay, opto-receiver delay, transistor driver delay). Due to the fact that the signal delay is very small (below 1 microsecond) in most cases can be neglected. Thus, subsystem “Driver board” in most cases can be deleted at all. It minimises number of elements in model that increase speed of simulation.

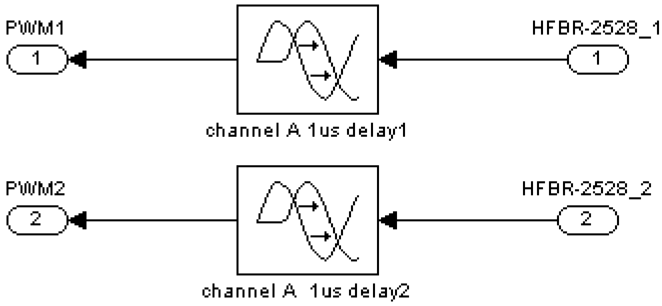


Fig.3.6. Driver board subsystem model

3.1.4. Model of Control board

Control board subsystem represent control device. Example of “control board” subsystem is given on figure 3.7. There is shown control algorithm for inverter.

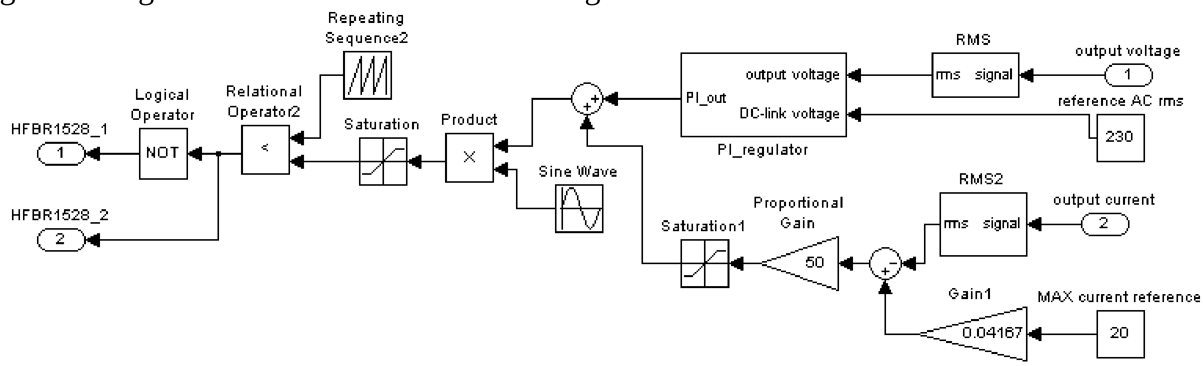


Fig.3.7. Example of control board subsystem model

3.2. Development of model of photovoltaic panel

To simulate power converter for PV panel the PV panel model is necessary. In Matlab-simulink toolboxes there is no PV model. Due to this it was decided to develop it [18].
It was used Matlab-simulink block “Controlled voltage source” that is controlled depending on input parameters like current and illumination [24,25]. To develop precise model of the PV panel using “controlled voltage source” it is necessary to know precise relation of it voltage and current.
PV panel V-I curve was measured experimentally and using regression methods was found formula that precisely describe real PV panel V-I curve at full illumination:

$$U(i) = 20 - 0.5 \cdot i - 3.4105 * 10^{-12} * i^{16} \tag{3.1}$$

As well to formula (3.13) was added one more variable to take in to account light intensity:

$$U(i) = 36 \cdot \frac{333 \cdot k}{q} \cdot \ln\left(\frac{6.24 \cdot E}{I_0} + 1\right) - 0.5 \cdot i - \frac{3.4105 \cdot 10^{-12} \cdot i^{16}}{E} \tag{3.2}$$

where: E – light intensity in fractions from experimental current at full illumination (6.24A). Practical illumination range is 0<E<2.
After that it was built PV panel subsystem in Matlab-simulink (fig.3.8).

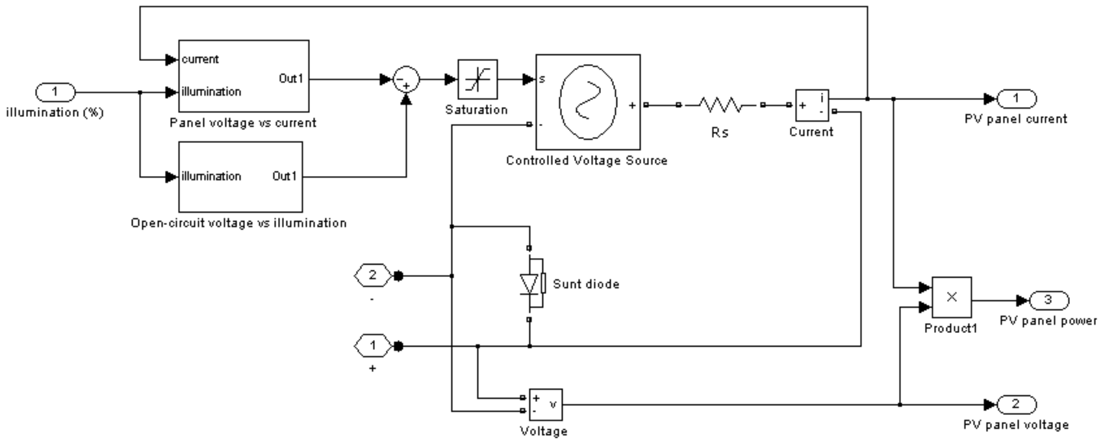


Fig.3.8. Matlab-simulink model of photovoltaic panel

There is voltage source controlled with the help of two functions. Subsystem “Open-circuit voltage vs illumination” (fig.3.9) represents the first term of equation (3.2). Series resistance “R_s” represents the second term of equation (3.2). Subsystem “Panel voltage vs illumination” (fig.3.10) represents the third term of equation (3.2).

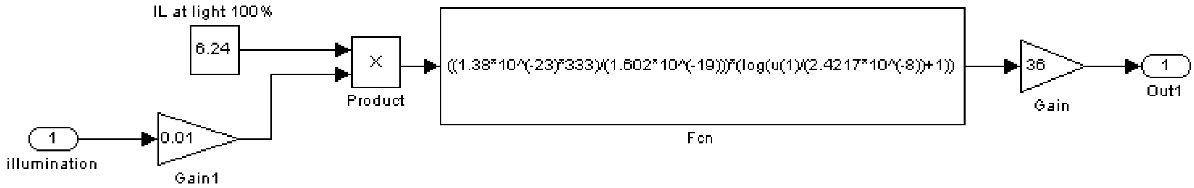


Fig. 3.9. Subsystem that represent open circuit voltage dependence on illumination

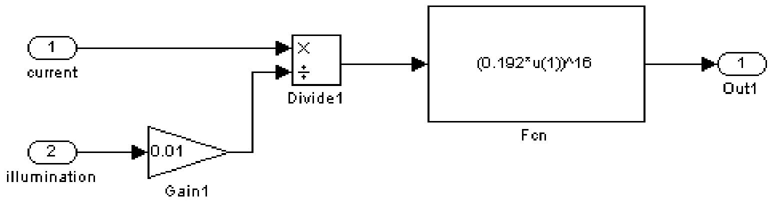


Fig.3.10. Subsystem that represent voltage dependence on current

Comparison of experimental and simulated data is given below on fig.3.11.

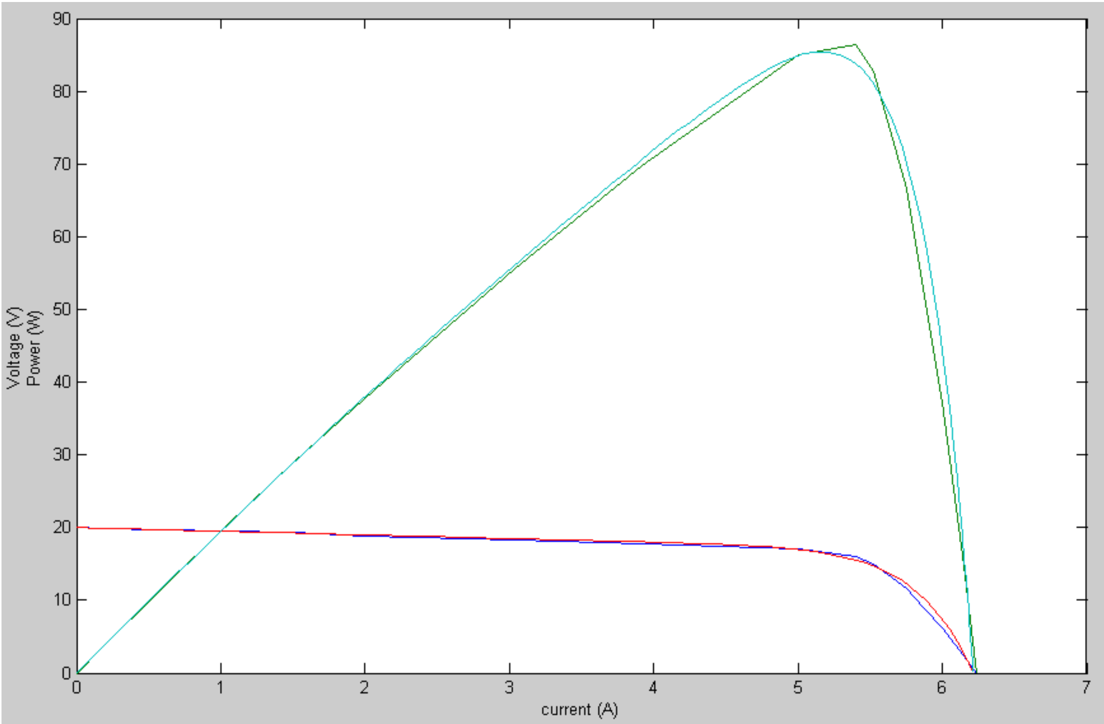


Fig. 3.11.Comparison of experimental and simulated data (at 100% illumination) of PV panel's I-V and I-P curves: (dark blue - experimental I-V curve, red - simulated I-V curve, green – experimental I-P curve, light blue – simulated I-P curve)

4. Development of UPSS based on Versatile power module

4.1. Simulation of Inverter

There are two conventionally used types of inverter:

- Half-bridge
- Full-bridge

Both these types of inverters have advantages and disadvantages. The half-bridge inverter has high DC-link voltage, but due to small number of semiconductor it can have higher efficiency. The full-bridge inverter has 2 times lower DC-link voltage, but it has two times more semiconductors. To find inverter topology that fits well both inverters topologies were simulated. The example of full-bridge inverter simulation is shown.

The full-bridge inverter simulation

To assemble the full-bridge inverter the two VPMs are necessary (fig. 4.1.)

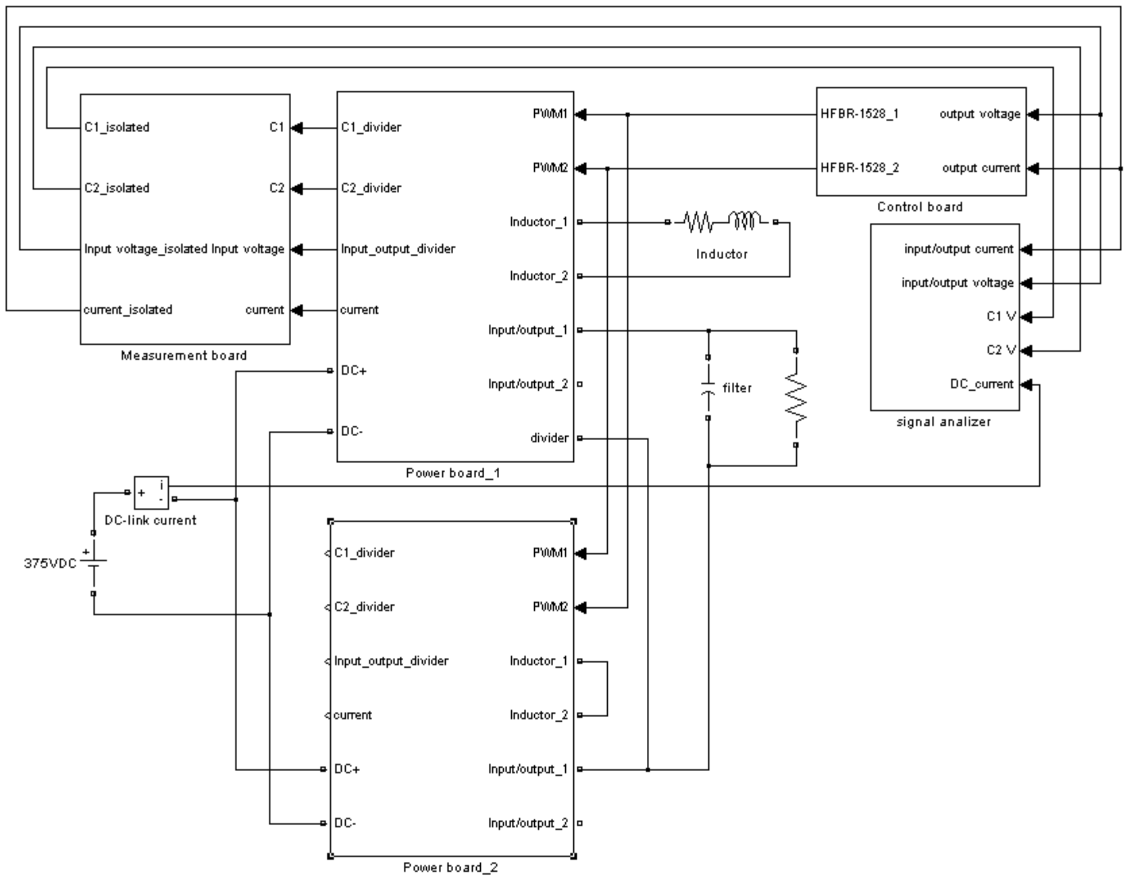


Fig.4.1. Matlab-simulink model of full-bridge inverter

Control algorithms is depicted in fig.4.2. There are the output voltage and the output current measured in this scheme. Output current is measured to prevent overload and short circuits.

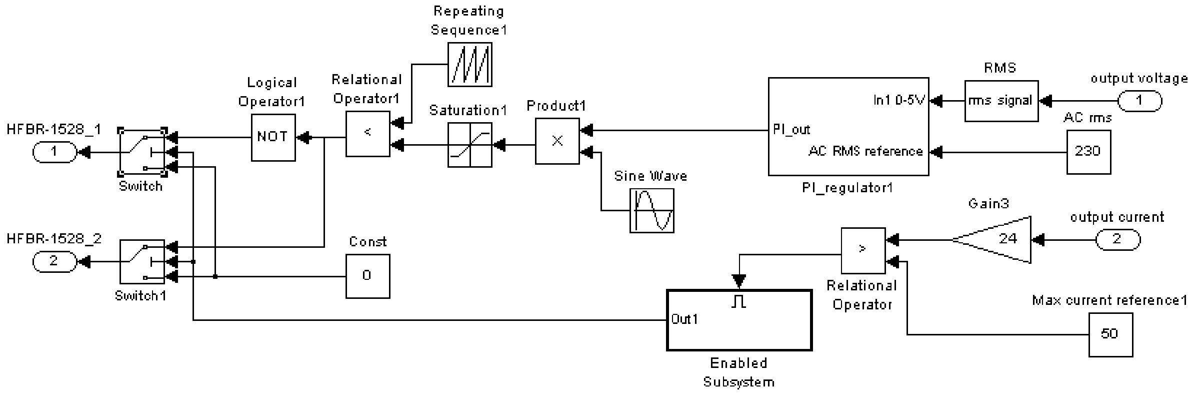


Fig.4.2. Full-bridge inverter control system with 2 feedback signals

Simulation results are given for output power 4000W in figure 4.3.

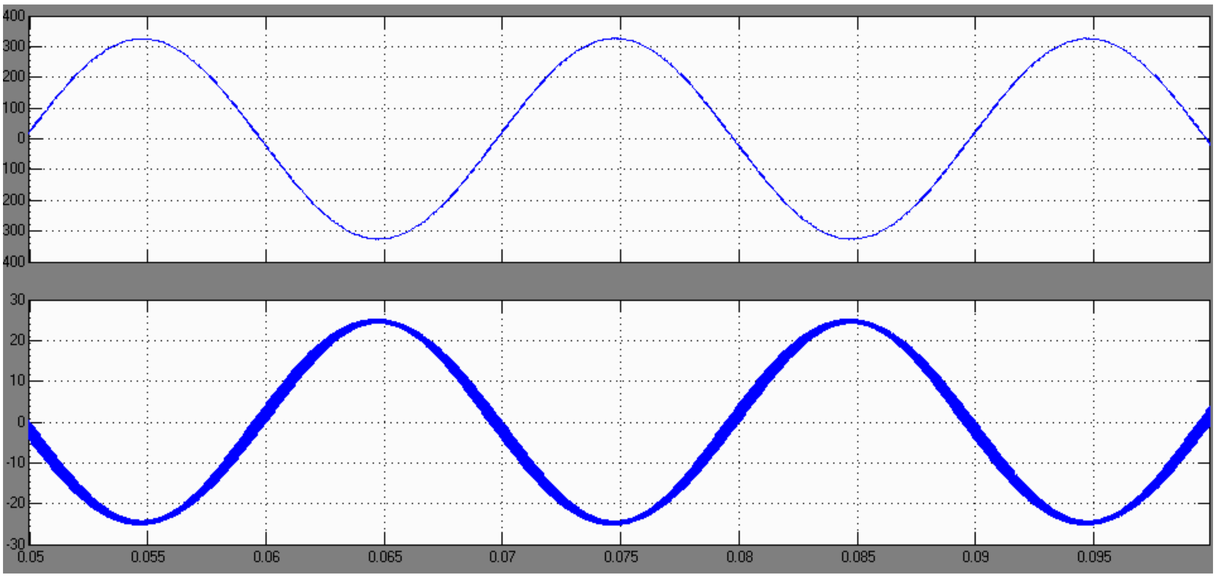


Fig.4.3. Simulation results at 4000W. Upper curve is load voltage, but lower is inductor current. The inductor current THD is 5.2%. But due to additional output filter (4.7uF capacitor) load current has THD about 1%.

Simulation data for different loads are given in table 4.1.

Table 4.1. Simulation results of full-bridge inverter with different loads

Power (W)	Current (A)	Output voltage THD (%)	Converter efficiency (%)
1000	4.5	0.8	96.5
2000	8.7	0.8	96.8
3000	13.1	0.8	96.7
4000	17.5	0.8	96.4

Simulation results in table 4.1. shows relatively higher inverter efficiency. Reasons of such results can be idealized Matlab-Simulink models of semiconductor devices. It doesn’t take in to account torn-on losses. From this can be concluded that simulated efficiency will be higher that real converter efficiency.

4.1.1. Simulation of Active PFC Rectifier

These are many different topologies of rectifiers with PFC. To find better PFC rectifier topology for uninterruptible power supply system six of them were simulated and compared. The boost PFC topology simulation example is given below.

a) Boost PFC topology

Boost PFC topology is most popular topology of active PFC rectifiers. It is often used for high power factor rectifiers in power supplies and electric drive applications.
The line current simultaneously flows through three semiconductors that is the most significant disadvantage of boost PFC. For this reason the overall efficiency of such converters usually is lower than that oh the other topologies.
Matlab-simulink model of the boost PFC converter is shown in Fig. 4.4. For this converter simulation one versatile power converter plus one diode-bridge rectifier are used.

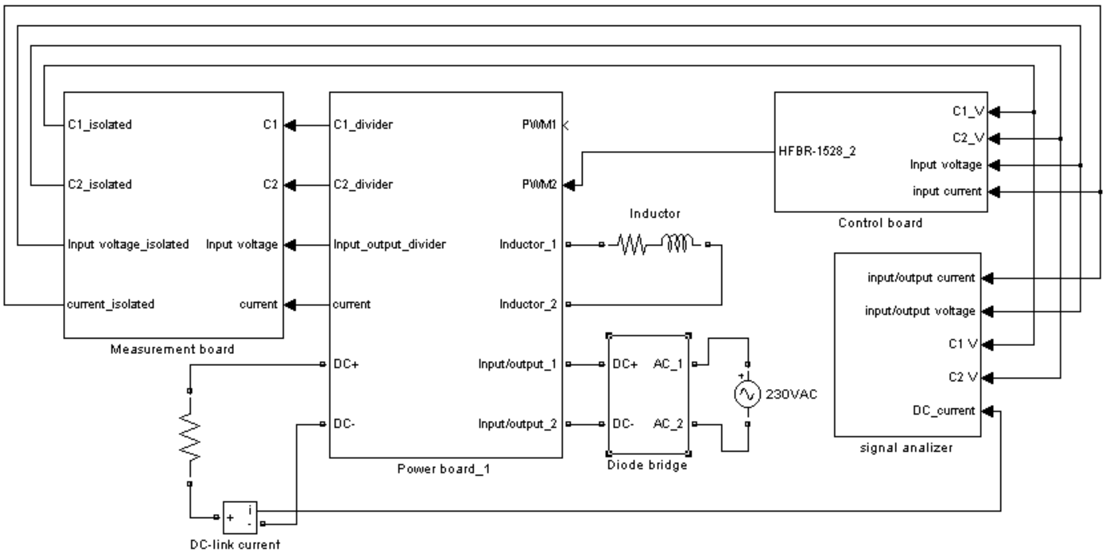


Fig. 4.4. Matlab model of subsystem “power board” for boost PFC converter

The following are connected to the versatile power converter:

- AC voltage source (230V rms) that simulates the grid
- Diode bridge that rectifies grid voltage
- Inductor (L -2 mH, resistance - 0.13 Ohm)
- Variable resistive load to get different powers and input currents
- Auxiliary current measurement blocks “DC-link current” that are necessary only for output power metering and converter efficiency calculation

Control signal of boost PFC converter can be calculated using next formula:

$$d(t) = 1 - \frac{\hat{V}_s \cdot |\sin(\omega t)|}{V_d} \tag{4.1}$$

where : d – duty cycle, V_d – DC-link voltage, $\hat{V}_s$ - input voltage amplitude value, The control circuit of boost PFC is given in fig. 3.26. As a feedback is used the DC-link voltage that have to be regulated close to 375V. Also the control algorithm has protection from DC-link over-voltage and transistor over-current. In the case of exceeding one of the limits the transistors switches-off.

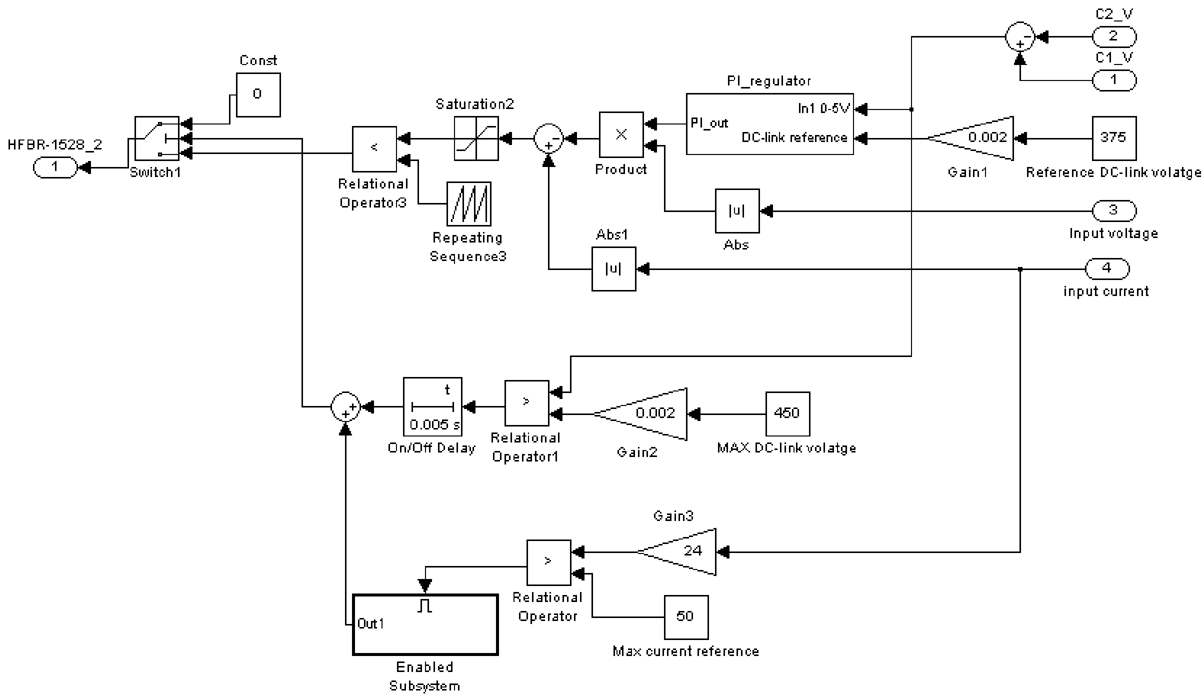


Fig. 4.5. Matlab-simulink model of control board for boost PFC rectifier

Simulation results for are given in table 4.2. As can be seen from table the grid current is sinusoidal and in phase with voltage.

Table 4.2. Boost converter simulated data

Output power (W)	Input current (A)	Input current THD (%)	Converter efficiency (%)	Cos(f)
1100	5	13.6	96.7	1
2200	10	6.9	96.6	1
3300	15	4.7	96.2	1
4400	20	3.9	95.8	1

4.1.2. Simulation of Charge/discharge converter

As it was mentioned in the first chapter, there are different possible backup energy sources. In order to make the UPSS more flexible it is necessary to make the bidirectional DC/DC power converter to be able to work with any type of the DC energy source or DC energy storages. Next energy storages were available for experiments:

- Supercapacitor 48.6V, 165F, 0.007 Ohm
- Supercapacitor 125V, 63F, 0.018 Ohm
- Lead-acid battery, 6x12V=72V, 17Ah, 6x0.012=0.072 Ohm

As it was mentioned above there are two types of inverters: full-bridge and half-bridge. They have important difference: DC-link voltage of full-bridge inverter has to be close to 375V, but

DC-link voltage of half-bridge inverter has to be close to 750V. Using Matlab simulink possibility of building DC/DC converter for both levels of voltages with the above mentioned storages will be tested. Matlab-simulink model of the bidirectional DC/DC converter that can be assembled with versatile power modules is given on fig. 4.6.

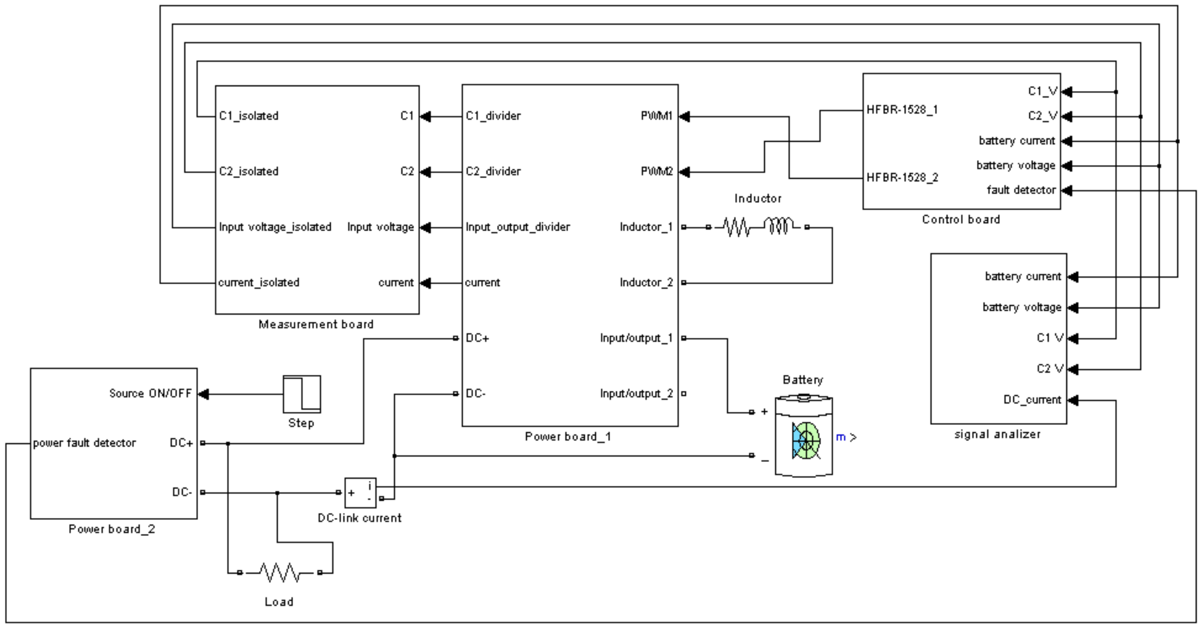


Fig.4.6. Bidirectional DC/DC converter Matlab-simulink model

To versatile power modules the following elements are connected:

- Energy storage (battery or supercapacitor)
- Inductor (L -1 mH, resistance - 0.05 Ohm)
- Voltage source that supplies DC-link and in the case of failure it gives failure signal to the control system
- Resistive load in DC-link
- Auxiliary current measurement blocks “DC-link current” that are necessary for output power metering and converter efficiency calculation

As was expected the Matlab-simulink simulations of different operation modes and with different energy storages shows that the 48,6V supercapacitor can not be used as an energy storage (due it low voltage and converter high input current) with above mentioned converter.
As the simulations didn’t take into account transistors thermal regimes it was decided as well to check thermals regimes of all configurations.
To calculate thermal regimes and losses of transistors and diodes it was used “Semikron” “Semisel” software [13]. In calculations is assumed that water temperature is $60C^0$ and heat sinks parameters taken from 2 chapter. All calculations are done for switching frequency 20kHz.
Calculation shows that it is not possible to boost 4.2kW with one versatile power module nor with 72V lead-acid battery nor with 125V supercapacitor.
Thus it was done calculations for two parallel connected VPMs. Calculations shows that 2 VPMs can be used to boost 4.2kW, but more preferable is configuration with DC-link voltage 375V. In case of higher DC-link voltage (750V) it is better to decrees switching frequency (down to 10kHz) it will reduce losses in transistor and diode.

4.1.3. Simulation of Power converter for photovoltaic array

Using the developed PV panel model in the third chapter the simulation of MPPT (maximal power point tracking) control algorithm was done. The versatile power converter was configured as the boost converter (fig.4.7.) and connected to its PV array that consists of 4 PV panels.
It can be assumed that the PV array voltage variation from illumination is not very high that means that maximal power point will be at definite voltage in most illumination levels. That allows to use such MPPT algorithms where are kept constant voltage of the PV array. For 4 panels connected in series the maximal power will be about 65 V.

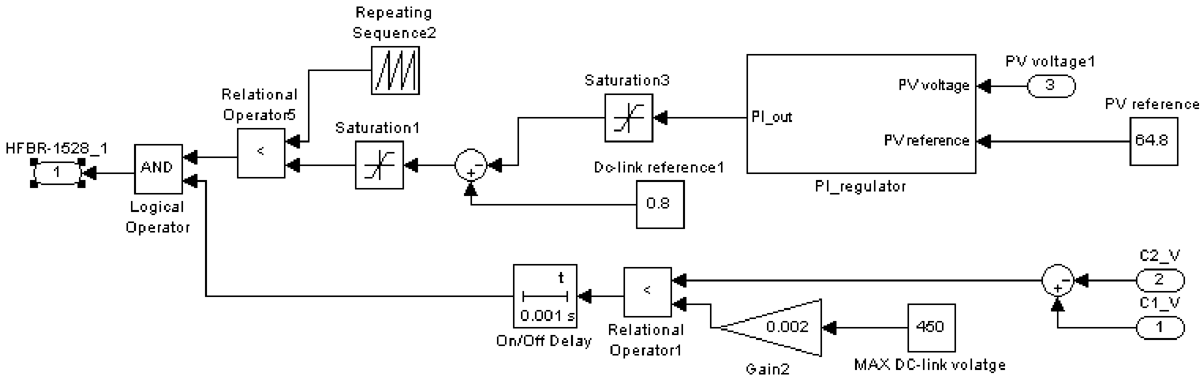


Fig.4.7. MPPT control algorithm

The simulation results have shown that the MPPT algorithm allows to utilize almost all PV array generated power.

Table 4.3. Comparison of PV array generated power and collected power by power converter with MPPT

Illumination level (%)	Generated	Simulated MPPT
100	342	340
50	177	170
120	404	402

4.1.4. "Online" UPS topologies and it simulation

In the previous chapters provide the descriptions of inverters and rectifiers and their simulations. From the converters description we can conclude that there are two possible voltage levels for UPS DC-link: with lower (375V) DC-link voltage and higher (750V) DC-link voltage. This means that the half-bridge inverter can be coupled only with half-bridge PFC rectifier, but full-bridge inverter can be coupled with another 5 mentioned PFC rectifiers. The boost PFC topology needs 1 versatile power converter and other topologies need 2 versatile power converters. To minimize number of the power converters number the boost topology was chosen for the second UPS topology. Both UPS topology configurations were simulated.

Matlab-simulink model of UPS topology with DC-link voltage 375V is depicted in figure 3.50. It allows to simulated different regimes of operation of "online" UPS. The simulations shows that output voltage is sinusoidal and doesn't depends of input voltage shape. Input rectifier current is sinusoidal. At rated power the current THD is near 4-5%. Input power cos(f) is near 1. Overall simulated efficiency of double conversion is 0.93.

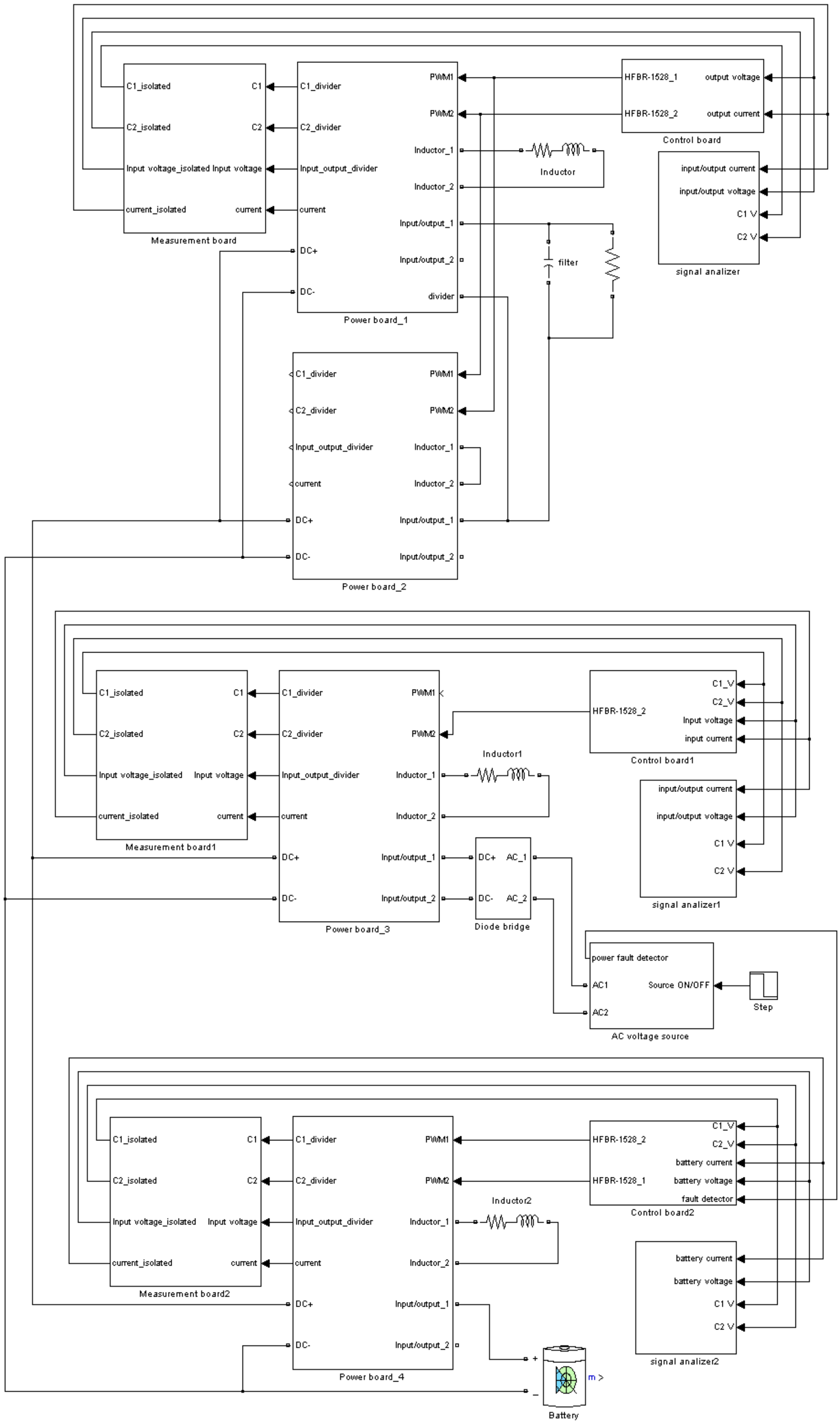


Fig. 4.8. Matlab-simulink model of “online” UPS with DC-link voltage 375V

4.2. Experimental approbation of versatile power modules

As it was mentioned, the simulation results can not be reviewed as precise results concerning to the converters efficiency. That is why it was decided to test experimentally most of the above mentioned converters topologies. Real-time controller system “dSpace DS1103” was used for this purpose. This is a laboratory tool for converter control and testing. It has many digital inputs and outputs, many ADC inputs, DAC outputs, PWM outputs etc. It is connectable to personal computer and compatible with Matlab-simulink. Thus the control algorithms from Matlab-simulink with slight changes can be used to compile code for “dSpase” system.

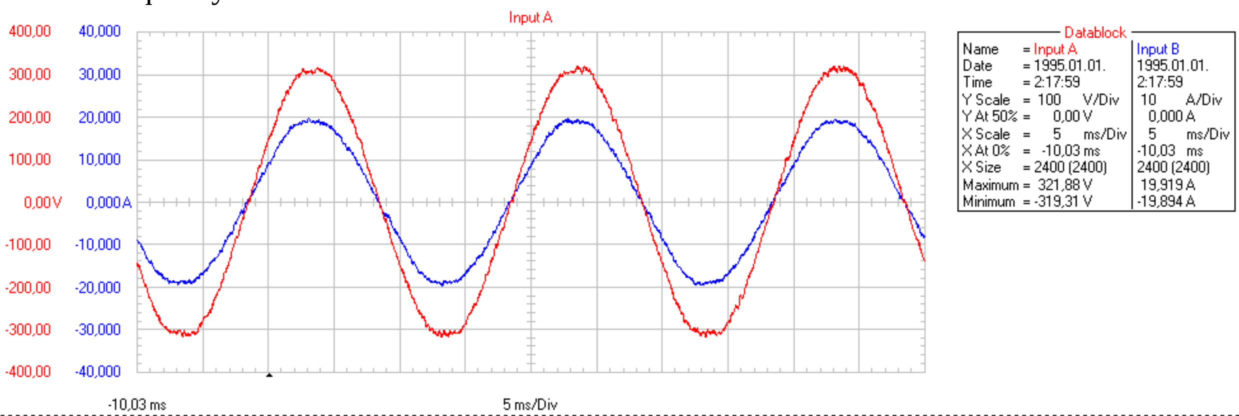
Additionally to “dSpace” program “dSpace ControlDesk” can be used that allows to build visual control interface to:

- see measured feedback signals like on oscillograph
- control and change reference signals
- follow to control signals
- etc

4.2.1. Rectifier testing

Using one versatile power module it were done experiments with boost PFC rectifier.

Example of experimental input current and input voltage of boost PFC rectifier are given on fig.4.9. The current spectral analysis is given on fig.4.10. Such input current harmonical distortions qualify the EN 50160 standard.



`7, DC=377,1V, Rload=50 Ohm, Uin=223, Iin=13,9A`

Fig. 4.9. Experimentally measured date of boost PFC converter at 75% of nominal load (red – input voltage, blue – input current). Current THD= 2.2%, cos(f) close 1.

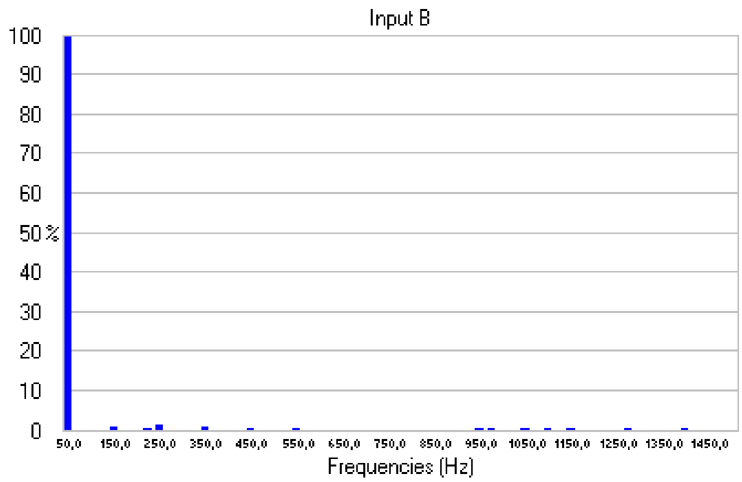


Fig.4.10. Current spectral analysis of boost PFC converter at 2.8kW

The table 4.4. present data with different loads.

Table 4.4. Experimentally measured data

Output power (W)	Input current (A)	Input current THD (%)	Converter efficiency (%)	Cos (f)
706	3.4	7.2	93.7	0.99
2144.3	10.1	4.1	93.1	0.99
2842.6	13.7	2.2	92.6	0.99

In case if the experimental and simulated data are compared it can be seen that they have the difference in efficiencies. This is because imperfection of Matlab transistor model. Mostly it can calculate conduction losses, but switching losses it calculate incorrectly.

In similar ways were tested other PFC topologies. Experimental data shows that other PFC topologies can also consume sinusoidal current from the grid. The highest efficiency has shown bridgeless topology. It must be noted that accuracy of voltage measurement device is ±0.5% and accuracy of current measurement device is ±2.5%. So, power accuracy is in the range of ±3%. Unfortunately more precise calculation can not be done with existing laboratory equipment.

4.2.2. Inverter testing

At the given time there is lack of laboratory high voltage DC voltage source (800V, 5A) and due to this it was tested only full-bridge inverter.

Experimentally measured current and voltage of full-bridge inverter with linear load are depicted on fig.4.11. Inverter output RMS voltage is 226V. There was used 12.5 Ohm resistance that why the load power is 4 kW. Efficiency of voltage inversion was about 95%.

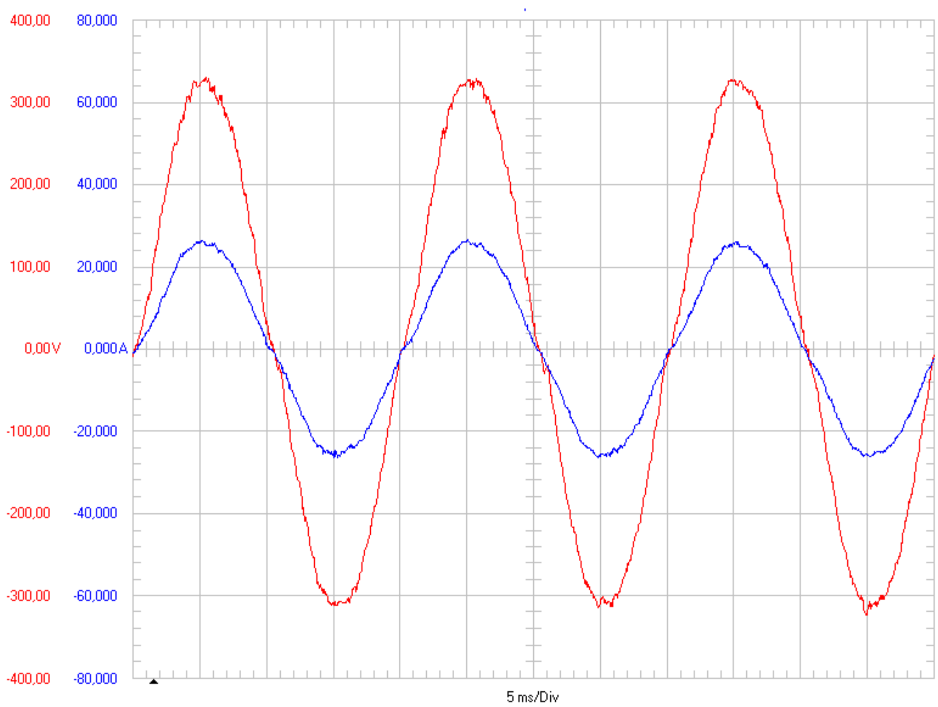


Fig. 4.11. Inverter current and voltage with linear load (current – 20A/div, voltage – 100V/div)

Spectral analysis of inverter voltage. is given on fig.4.12. THD of inverted voltage is 4%.

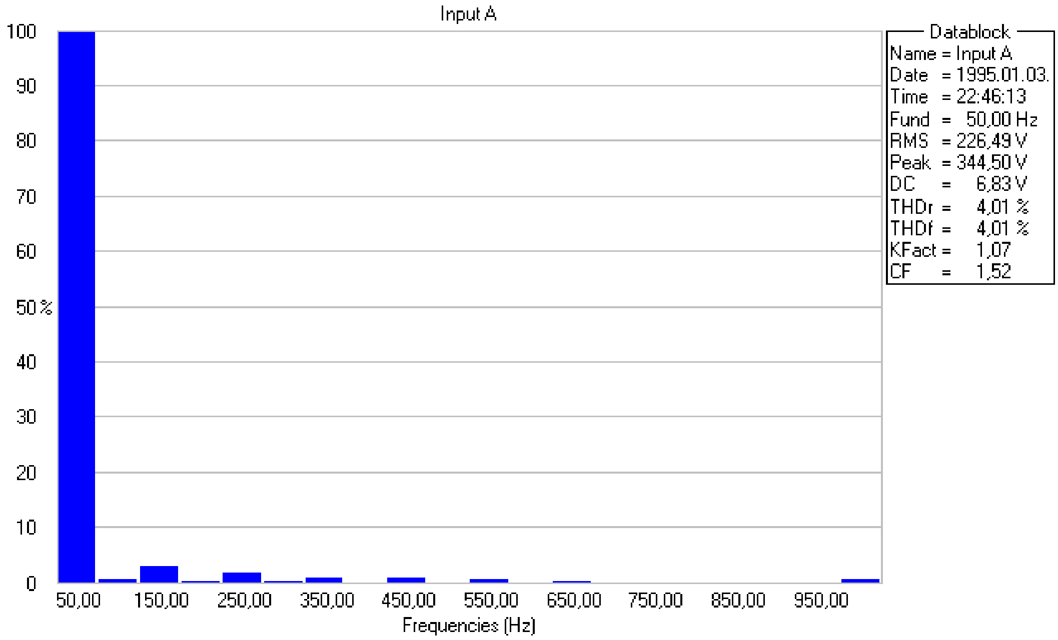


Fig. 4.12. Loaded with linear load inverter voltage spectral analysis

Experimentally measured current and voltage with non-linear load are depicted on fig.4.13. RMS value of current is 7.7A. Voltage RMS is 209V.

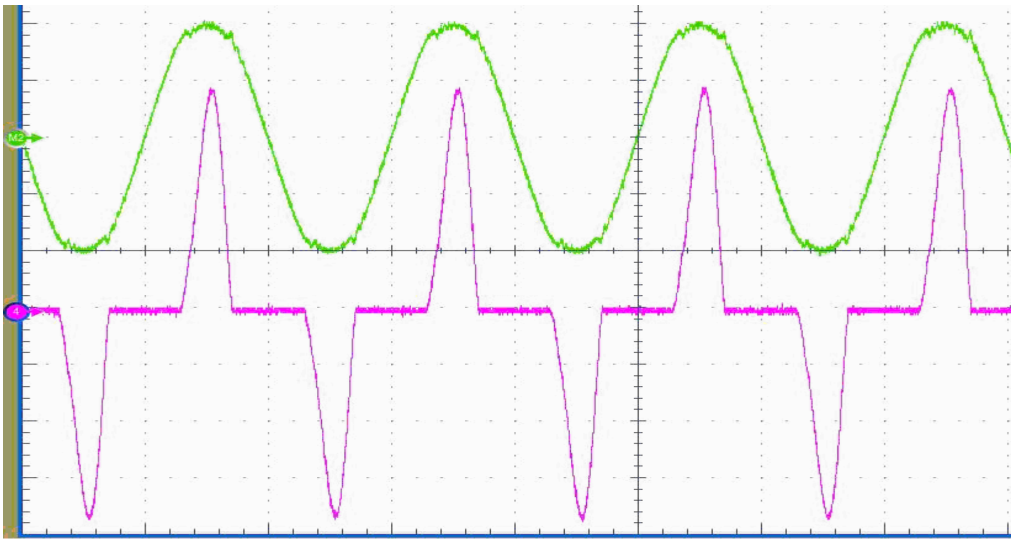


Fig. 4.13. Inverter current and voltage with non-linear load (current – 5A/div, voltage – 150V/div)

4.2.3. Online UPS testing

After the separate converter testing "on-line" UPS was experimentally tested. For this purpose "online" UPS topology with DC-link voltage 375V was used. Its realisation needs 4 versatile power modules as a minimum. As a control device the "dSpace" module was used.
Fig. 4.14. represents "online" UPS operation with rated voltage (220V-230V) and at 50% of the rated power. The figures show that output voltage does not depends on input voltage shape and amplitude. It is obvious that input voltage shape is distorted due to many nonlinear loads in RTU grid (voltage THD about 8%), but the output voltage is corrected and it THD is about 3-4%. Experimental test with undervoltage (180V) and overvoltage (250V) also were

done and they have shown that output voltage does not depends on input voltage magnitude also.

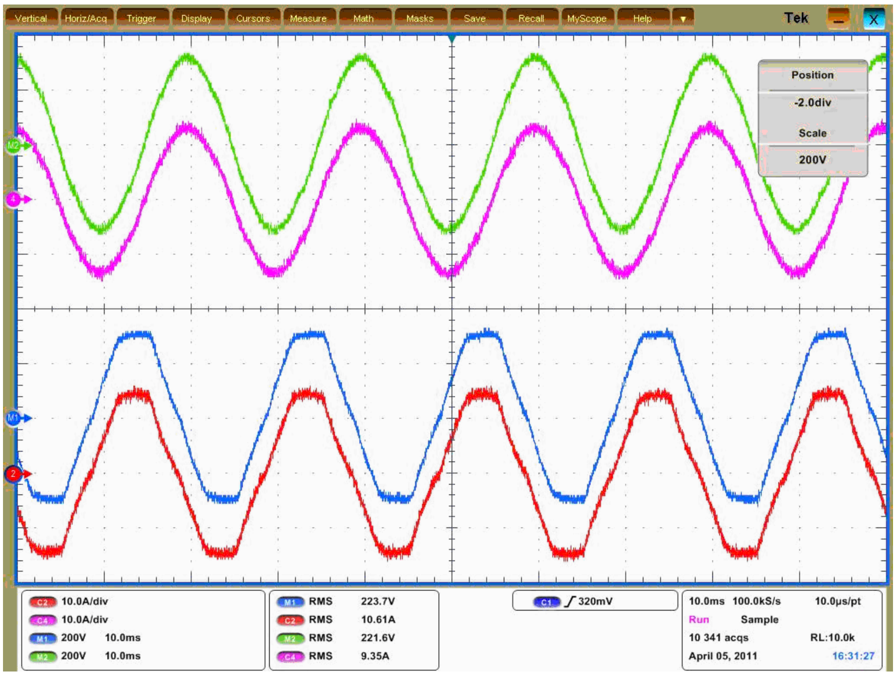


Fig. 4.14. UPS voltages and currents with rated input voltage.
(Input voltage-blue, input current- red, output voltage - green and output current – purple)

The next pictures represent operation of assembled “online” UPS with non-linear load. As it can be seen the input current is sinusoidal.

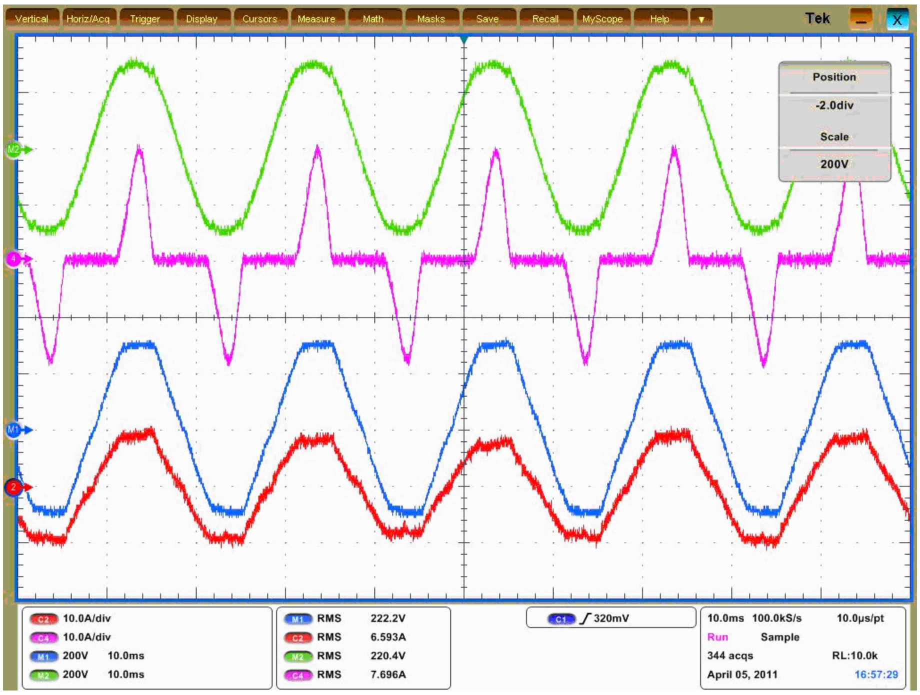


Fig. 4.15. UPS voltages and currents at rated input voltage and non-linear load.
(Input voltage-blue, input current- red, output voltage - green and output current – purple)

Another important parameter of UPS is switching time to backup storage. For these reasons the control algorithm also has subsystem “Power failure detector”. It is necessary to detect the presence of input voltage and in the case of power failure it switches the UPS to backup storage mode.
The “power failure detector” was experimentally tested. Fig.4.16 demonstrates that detection time is close to 5ms. The operation of “power failure detector” in UPS are depicted on fig.4.17.

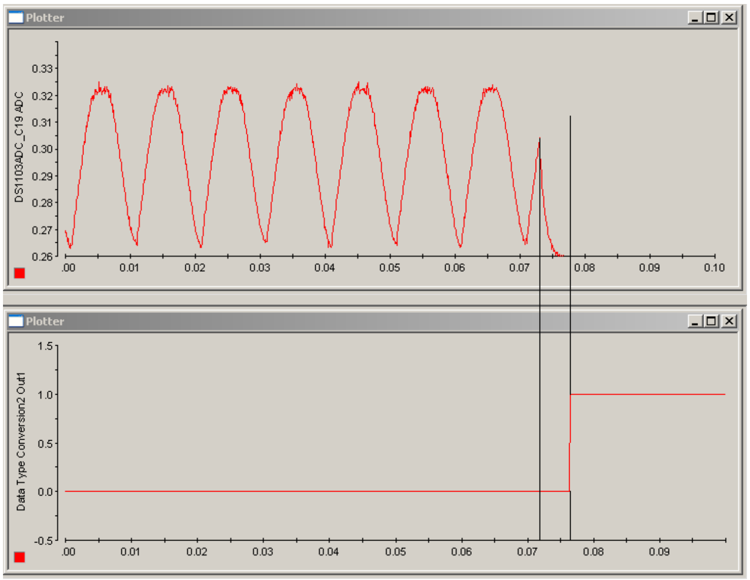


Fig.4.16. Experimental test of “Power failure detection” detection time is near 5ms.

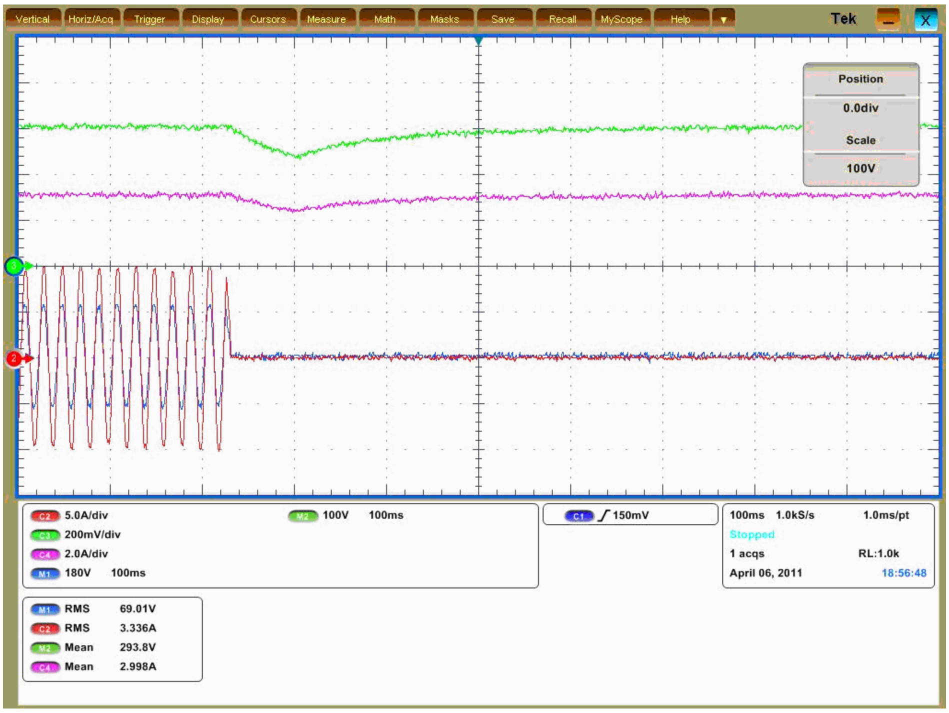


Fig.4.17. Operation of “power failure detector”

5. Cost of Versatile power module

This chapter present cost comparison of classical UPS systems and UPS that is built with VPM. As it was mentioned with 5 VPMs can be assembled 4kW online UPS. The cost of such UPS is near 1890Ls. Classical “online” UPS cost approximately 1500Ls [www.powerall.lv].

As can be seen the price of developed UPS system is higher. Main reason that it is cost of prototype. In case of mass production this price can reduced 30% or even more.

But main reason is that VPM are developed for more complicated tasks that can not by realized with UPS that’s represent on the market.

Major results

- Uninterruptible power supply system that allows to utilize varied energy sources and storages has been proposed and developed
- Versatile power module for uninterruptible power supply system has been developed
- MATLAB-Simulink models of the proposed UPSS and its elements have been proposed, developed and validated
- Several configurations VPM based UPSS with varied energy storages and sources have been tested

Minor results

- As a result of secondary research it was developed precise Matlab-Simulink model of photovoltaic panels that are available in "Institute of Industrial Electronics and Electrical Engineering " laboratory that can be used in future researches too
- As a result of secondary research it was developed cheap and robust construction of primary hear sink for water cooling system

Conclusions

- The proposed approach of development of UPSS provides increased flexibility of utilization of alternative sources and storages

- The proposed VPM provides effective laboratory test bench for research and development of the proposed UPSS

- The utilized simulation-testing environment based on MATLAB-SIMULINK-dSpase(CP1103) even more facilitates development of UPSS hardware and software

- Simulation and experimental results prove initial assumption of easy reconfigurable versatile concept of UPSS development

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