**LAPPEENRANTA UNIVERSITY OF TECHNOLOGY**
DEPARTMENT OF ELECTRICAL ENGINEERING

# MICROGRIDS AND THEIR OPERATIONS

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# ABSTRACT

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Interconnection of loads and small size generation forms a new type of distribution systems, the Microgrid. The microgrids can be operated together with the utility grid or be operated autonomously in an island. These small grids present a new paradigm of the construction of the low voltage distribution systems. The microgrids in the distribution systems can become small, controllable units, which immediately react to the system's changes. Along with that the microgrids can realize the special properties, such as increasing the reliability, reducing losses, voltage sag correction, uninterruptible supplying.

The goals of the thesis are to explain the principles of the microgrid's functioning, to clarify the main ideas and positive features of the microgrids, to find out and prove their advantages and explain why they are so popular nowadays all over the world. The practical aims of the thesis are to construct and build a test setup of a microgrid based on two inverters from SMA Technologie AG in the laboratory and to test all the main modes and parameters of the microgrid's operating. Also the purpose of the thesis is to test the main component of the microgrid - the battery inverter which controls all the processes and energy flows inside a microgrid and communicates with the main grid.

Based on received data the main contribution of the thesis consists of the estimation of the established microgrid from the reliability, economy and simplicity of operating points of view and evaluation of the advisability of its use in different conditions. Moreover, the thesis assumes to give the recommendations and advice for the future investigations of the built system.

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# ABBREVIATIONS AND SYMBOLS

## Roman letters

| | |
|---|---|
| $f$ | frequency [Hz] |
| $\cos(\varphi)$ | power factor |
| $I$ | current [A] |
| $U$ | voltage [V] |
| $P$ | active power [VA] |
| $Q$ | reactive power [VAR] |
| $Z$ | impedance [Ohm] |
| $R$ | resistance [Ohm] |
| $X$ | reactance [Ohm] |
| $L$ | inductance [Vs/A] |
| $C$ | capacitance [Is/A] |
| $F$ | feeder flow [VA] |

## Greek letters

| | |
|---|---|
| $\delta$ | power angle [rad] |
| $\omega$ | angular frequency [rad/s] |
| $\psi$ | phase angle difference [rad] |
| $\Theta$ | rotation angle [rad] |

## Acronyms

| | |
|---|---|
| CHP | combined heat and power |
| RES | renewable energy sources |
| DG | distributed generations |
| PCC | point of common coupling |
| MGCC | microgrid system central controller |
| MC | micro source controller |
| LC | load controller |
| DNO | distribution network operator |
| MO | market operator |

| | |
|---|---|
| AC | alternating current |
| DC | direct current |
| VSI | voltage source inverter |
| HV | high voltage |
| SMO | single master operation |
| MMO | multi master operation |
| EMI | electromagnetic interference |
| MOSFET | metal-oxide-semiconductor field-effect transistor |
| IGBT | insulated gate bipolar transistor |
| PWM | pulse width modulation |

# 1 Introduction

## 1.1 Microgrid. Definition and operating

The need of reducing $CO_2$ emissions in the electricity generation field, electricity markets restructuring and technological development in the microgeneration lead to the growing interest in the use of microgeneration. Microgrid is a new type of power systems consisting of generation sources, loads and energy storages. In another words, it is an association of a small modular generation system, a low voltage distribution network and load units interfaced by means of fast acting power electronics.

Microgrids are determined usually in accordance with a few definitive functions. They are usually used in small urban areas or in small industry. The most common power range for microgrids is from 25 to 100 kW. But the systems with lower and upper power levels are also widely used. As micro energy sources in microgrids, usually, diesel or gas motor driven gensets, fuel cells or renewable generation such as wind parks, photovoltaic systems and gas or biofuel driven micro turbines are used. [1]

The generating technologies which are used in microgrids have potentially lower cost and lower emissions in comparison with traditional power sources. This assumption is based on the idea of generating heat and electrical power simultaneously in the units. The smaller size of these generating units allows them to be placed in the best position for cooling, energy distribution and maintaining of the installation. The most appropriate way to realize the rising potential of small scale generation is to tie loads and generating units together. This is accomplished in microgrids by using inverters to interface generating units with the distribution system. Such applications can increase the efficiency of the system remarkably, especially if the thermal power of the system may be utilized for heating buildings. [14]

Microgrids operate in two basic modes. They can operate in off-grid mode. In that case the power is generated and stored without assistance from the main low voltage grid. These microgrids comprise one or more energy sources, batteries and local loads which are fed by these sources. In other case a microgrid is connected to the main grid in normal interconnected mode. This operating manner, usually called grid-connected mode, is the main operation mode. In this mode microgrid operate as a back-up system or as a part of the utility system. The purpose of the back-up microgrid system is to feed local loads when the main grid fails for any reason. This mode is also called the emergency mode. The configuration of a microgrid in the grid-connected mode also requires a power source and a large battery bank. Batteries or super capacitors are used in microgrids for storage the excess of the generated energy and support energy sources when the loads increase. The size and type of the batteries are determined by system’s requirements. During the normal operation of the main grid, the purpose of the microgrid is to maintain the battery bank in full charged condition so that it should be always ready for emergency operating. When microgrid operates like a part of the utility system, the microsources of the microgrid feed local loads. If the generated power exceeds the demanded power level inside the microgrid, excess of the energy is supplied to the main grid. In the other way, if microgrid cannot provide full supplying of its local loads the required energy flows from the main grid. Due to the fact that most of the loads require AC power which is opposed to the DC power generated by the sources, the battery inverters intended to invert and control electrical energy flows are required in both operation modes. [1]

### 1.1.1 Functions of the microgrid units

The components of the microgrid system are recognized in accordance with their function. There are

- grid forming units
- grid supporting units
- grid parallel units.

The grid forming units are able to control the voltage and frequency of the grid by balancing the power of the loads and generators. Among the grid forming units are the diesel generators and battery inverters. The grid supporting units are simple control units. Their active and reactive power simply depends on the voltage and frequency characteristics of the systems.

Loads and uncontrollable generators such as wind energy converters and photovoltaic systems form the group of the grid parallel units. The main aim of these generators is to produce as much power as possible. [13]

### 1.2 New generation technologies used in microgrids

There are many different kinds of the generation technologies for microgrids. Among them are the internal combustion engines, gas turbines, microturbines, photovoltaic, fuel cells and wind-power technologies. Beside them many new technologies have emerged during the latest years. The most common new generation technologies are gathered in this chapter.

A wind-electric turbine generator converts wind energy to electric energy. The main part of the wind-electric systems is a blade, usually called rotor. The wind-electric turbine generator uses air to move the blades. The air pressure is small therefore the diameter of the blades should be large. In normal environments 1kW wind turbine blade’s diameter is approximately 2.6 meters. The wind-electric turbine generator comprises also a gearbox, generator, control electronic equipment, grounding and interconnection equipment. The rotor is placed on a high tower. Nowadays the wind-electric systems are widely spread in the world. It is enough to find a windy area to generate electricity economically. [20]

Photovoltaic systems convert the Sun energy into electricity. A photovoltaic module or solar panel is a group of many solar cells. The solar cell is a device that uses photons from the Sun to make the electric charges which are the basis of the electric current. There are many benefits of using the photovoltaic systems. The modular construction of the photovoltaic systems allows them to be installed very quickly in any place. The photovoltaic cells do not need cooling systems and the environmental impact is minimal in such systems. [21]

Micro-hydro power plants are also widely used in the micro generation. There are two types of the turbines in the micro-hydro generation. In high head power plants the most common turbine type is so-called Pelton wheel, where a lot of cups are attached to the turbine, the water press down to the cups and as a result the turbine revolves on its axis. The other type of the micro-hydro turbines suitable for low head plants is so-called axial flow Kaplan turbine, where the hub of the turbine lies in the same direction with the water flow. The main advantage of the hydro power turbines is that they generate power permanently although of course the water flow changes a little bit during the seasons. The problem of the micro-hydro plants is at the constructing phase: how to construct the turbine with the minimal price and minimum environmental damage. [21]

Generating stations using natural-gas are, due to their low air emission, lower price and availability, the most suitable in microgrid systems. But diesel-fueled generating systems still dominate in short-run applications or as reserve energy resources. Natural-gas system’s emission has decreased permanently by improving design and control of the combustion process. Advanced natural-gas applications achieved nitrogen oxide producing level lower than 50 ppmv, which is a huge step forward in protecting the environment, but most of these systems still require to use the exhaust catalyst which decrease significantly system’s efficiency. Unfortunately it is still impossible to have high efficiency and low emission simultaneously in those systems. [13]

Microturbines are power plants where the generator is a rotating field machine, often a permanent magnet machine which operates at a high inconstant speed. It is a very important new generation technology. Microturbines consume different types of fuel including natural-gas, gasoline and other liquid or gaseous fuels. The NOx emission of this type of plants is less than 10 ppmv. But due to the very variable speed of the microturbines complicated power electronic methods are required to interface those systems to the grid. On the other hand the electricity producing efficiency of micro-turbines is low, typically in the range of 20 % of the fuel efficiency. If expencive and sophisticated recuperator technology is used the efficiency may rise significantly. Anyway 70 … 80 % of the fuel energy is converted to heat and there has to be a need for this heat to operate micro-turbines lucratively. [13]

Fuel cells are the systems which use hydrogen as a basic fuel for producing electricity. Currently phosphoric acid, temperature solid-oxide and molten-carbonate cells are used and become available in commercial interests. These systems have a very low emission and high efficiency compare to other generating plants but the technology of manufacturing of those systems is much more expensive. [13]

Stirling engine is a piston heat engine. It can be classified as an external combustion engine. The action principle of these engines is based on a heated air pressure. It is a very economical engine and also the environmental impact is not so large. [21] The problems in the Stirling engine are related to the stresses in the heat exchanger materials. Manufacturing difficulties have caused that the machine type is not so popular.

Diesel gensets are based on a diesel internal combustion engine. The principle of operating of the diesel genset is to convert the mechanical power of the diesel engine to the electrical power by using the electrical generator. The diesel gensets are widely used nowadays. These generating units do not need the special installation conditions and place. But due to the fact, that the environmental impact of the diesel engines is a very large, their usage decreases. [21] Table 1 presents the main parameters of the most-used energy sources in the microgrids.

Table 1. The parameters of the renewable sources. [22]

| Parameter / Source | Efficiency | Lifetime | Resource availability | Total energy cost (€/kWh). Includes capital, financing, fuel and maintenance |
|---|---|---|---|---|
| Photovoltaics | 9-14% regarding to the power of the sunlight striking the device | 30 years | The sun’s energy is unlimited. But the amount of the generated energy depends on a system’s location, fogs and clouds. | 0.12-0.24 |

| | | | | |
|---|---|---|---|---|
| Microturbines | Electricity production efficiency 20%,<br>80% heat | 25 years | The stocks of the natural-gas resources are still large. The availability and cost of the gas depends on a location of the generating unit. | 0.24-0.58 |
| Stirling Engines | electrical efficiency 29%-35% | 100000 hours | Uses hydrogen, natural-gas, biogas. The stocks of the natural-gas resources are still large. The availability and cost of the gas depends on a location of the generating unit. | 0.2-0.4 |
| Diesel gensets | 40 – 50 % | 25000 hours | The stocks of the oil resources are still large. The availability and cost of the diesel oil depends on a location of the generating unit | 0.2-0.4 |
| Micro-hydro power plants | 60-80% regarding to the power of<br>water flow | 5-20 years | Water reservoirs are unlimited | 0.15-0.2 |
| Wind turbines | 98% | 20 years | Winds are unlimited | 0.15-0.4 |

| | | | | |
|---|---|---|---|---|
| Fuel cells | 40-50% electricity production,<br>50-60% heat | 40000 hours | Natural gas reservoirs are still large. The availability and cost of the oil depends on a location of the generating unit.? | 0.6-1.3 |

## 1.3 Market perspectives

Due to the facts that using combined heat and power (CHP) and renewable energy sources (RES) bring commercial advantages and improve the environment, distributed generation is increasing worldwide. Last year's (2006) turnover in the market of wind energy systems was at the level of €2.5 billion a year, photovoltaic system’s market turnover was about €1.2 billion a year with total power of all installed photovoltaic panels 1000MW. Small hydro power plants bring about €3 billion a year. Expected growth in the photovoltaic and wind energy markets is approximately 34 and 25 percents a year correspondingly. [17] In the future, microgrids will consist of a few city blocks, fed by many small, low emission and high efficient distributed generations (DG) connected by the telecommunicational systems. These microgrids will form the electricity delivery systems of the areas. Also sharp increasing of activities, more than 25% per year, in CHP markets is observed. [1]

## 1.4 Advantages and difficulties of microgeneration

Microgrids have much smaller environmental impacts than traditional large thermal or hydro stations. Using of microgrids brings a reduction of gas emissions and helps in mitigating the climate change. According to the report “Microgrids-the Future of Small Grids” [11] decentralizing of power producing, see figure 1, brings the consumption of fossil sources of energy to a third compared to the present day status.

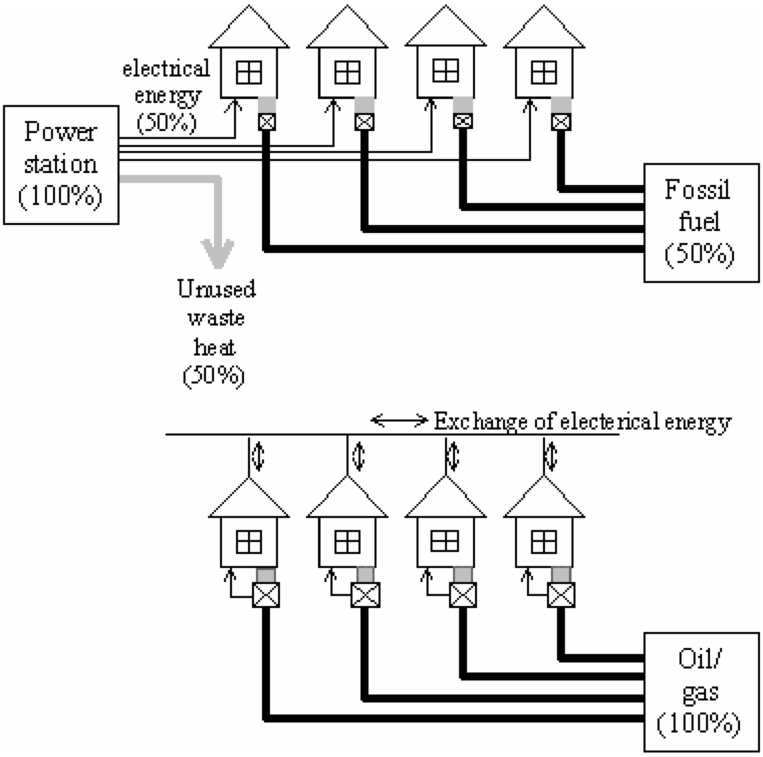

Figure 1. Energy economy in microgeneration. [11]

The most positive features of microgrids are the relatively short distances between generation and loads and low generation and distribution voltage level. Due to these factors the supply electricity security and reliability are increased, see figure 2, power losses in networks are reduced, costs on transmission and distribution decreased very much. It is not needed to invest in transmission and large scale generation. Based on this electricity prices are reduced because of transmission and distribution networks are used more extensively. [1]

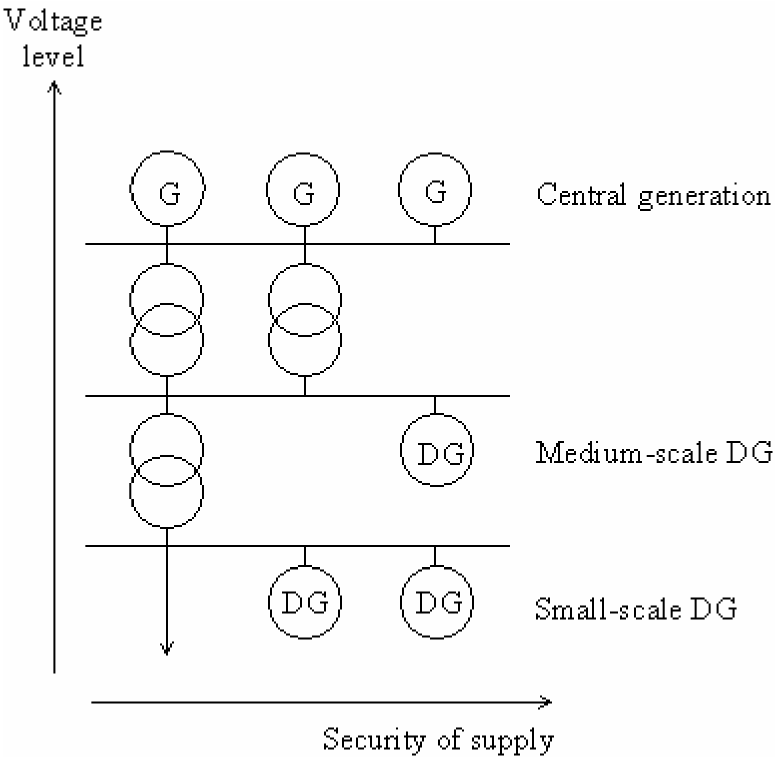

Figure 2. Security of supply vs. distributed voltage level. [11]

Despite of many advantages of microgeneration there remain many technical challenges and difficulties in this new power industry area. Microgeneration is lacking for experience, regulations and norms. Because of specific characteristics of microgrids such as strong interaction between active and reactive power, high implication of control components, large number of microsources with power electronic interfaces remains many difficulties in controlling of microgrids. Realization of complicated controlling processes in microgrids requires specific communication infrastructure and protocols. During the process of microgrid organization many questions concerning the protection and safety aspects emerge. How to take into account the market mechanisms to ensure efficiency, reliability and security of the system? Also it is required to organize free access to the network and efficient allocation of network costs. [1]

## 1.5 Microgrid concept and configuration

A microgrid contains two basic components; microsource and static switching power supply. Typical microgrid architecture with microsources is shown in figure 3. The system contains a group of feeders, which are also called distribution generations

(DG). The DG unit includes both a micro-source and a DC/AC converter. Microgrid also comprises a few groups of sensitive and non-sensitive loads, which represent a part of a distribution system. The part of the system which comprises the sensitive loads is required to be connected to the utility grid by means of using the static switch, see figure 3. It is needed to isolate the sensitive loads from the faults and other disturbances of the main grid. The single point of connection of the microgrid and the main grid is called point of common coupling (PCC). When the microgrid is connected to the main grid, in other words the microgrid operates in a grid-connected mode, the power from the microsources directly flows to the non-sensitive loads. But in case of faults or voltage sags in the main grid the microgrid has to transfer to island operation, that is to say it is required to disconnect the microgrid from the utility grid. This assumes the change in the output control of the generation units from a delivery power mode to frequency controlled operation mode along with the load needs. [7]

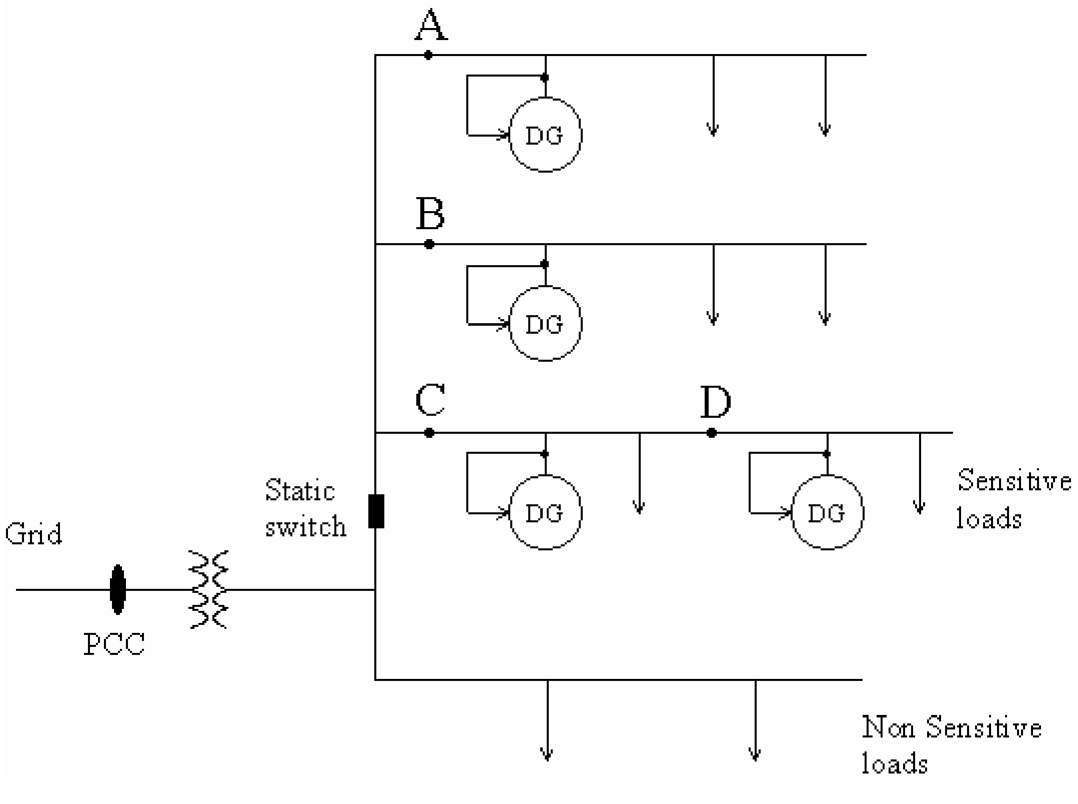

Figure 3. Microgrid architecture. [7]

## 1.6 The target of the thesis and its contributions

The main aims of the thesis are to explain the principles of microgrid’s functioning, to clarify the main ideas and positive features of microgrids, to find out and prove their advantages and explain why they are so popular nowadays all over the world. The practical aim of the thesis is to construct and build a test setup of a microgrid based on two inverters from SMA Technologie AG in the laboratory and to test all the main modes and parameters of the microgrid’s operating. Besides the target of the thesis is to compare the obtained results with the information which was received from different sources and articles. Also the aim of the thesis is to test the main component of the microgrid - the inverter, which controls all the processes and energy flows inside a microgrid and communicates with the main grid.

Based on received data the main contribution of the thesis consists of the estimation of the established microgrid from the reliability, economy and simplicity of operating points of view and evaluation the advisability of its use in different conditions. Moreover, the thesis assumes to give the recommendations of its using and advice for the future investigations of the built system.

# 2 Microgrid control

## 2.1 Basic in control of microgrids

As well as in the case of the utility grid the main aims of the microgrid are optimal using of feeding power and uninterruptible supplying of local loads. Basically a microgrid consists of a big number of different energy storages and generating units, microgrids are usually optimised for the different operation aims, one can be optimized for market participation and another can be destined for supplying uninterrupted domestic loads. This mean that the microgrid concept is required to achieve an autonomous control and a continuous operating of the systems even in case of loss of any components or generators and to provide unhindered connection of the additional microsources. A microgrid should be open so that new equipment may be connected to the grid. Anyone should be able to connect his own generating, load units or additional subsystems. In other words, it should operate and be able to be changed without support from engineers. It is called that the system possesses “plug and play” properties. [9]

These basic and specific properties are realized by microgrid’s power electronic control systems. Each unit of the grid provides a set of functions under managing from the power electronic control devices. These control systems should be able to regulate the power flow on the feeders, regulate the voltage at each microsource and ensure that each microsource increases or decreases instantly its generating power according to the needs of the microgrid when the systems turns to island. [13] To satisfy the basic and specific properties which are stated above, a microgrid’s advanced control comprises of three control levels: local Micro Source (MC) and Load Controllers (LC), MicroGrid System Central Controller (MGCC) and Distribution Network Operator (DNO) or Market Operator (MO). Distribution network and market operators may not be the parts of the microgrid. They operate in low or medium voltage grids where more than one microgrid may exist, and provide operational and market functions of the whole system correspondingly. DNO and MO are required to be in close connection with the microgrid. It is ensured by the microgrid Central Controller (MGCC). The MGCC is required to promote technical and economical operation policy, provide set points to Load Controllers (LC) and Micro Source (MC) and interface with all other components of microgrid. Load Controllers (LC) control providing uninterruptible loads’ supplying. Micro Source controllers (MC) check the level of required generating power of microsources. A scheme of allocating control levels of microgrid is shown in figure 4. [10]

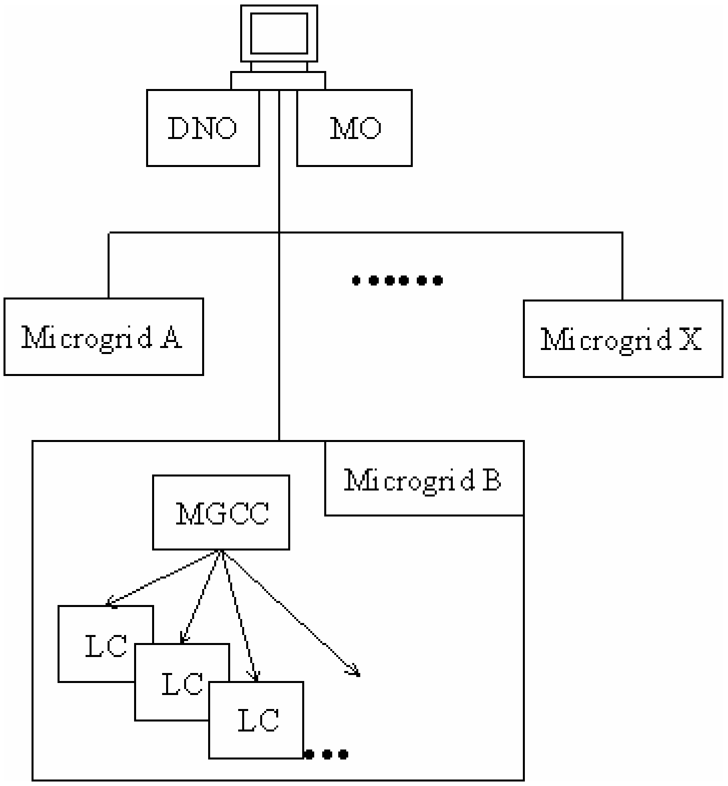

Figure 4. Control levels of the microgrid. [10]

Realizing of “plug and play” properties (see part 2.1) in microgrids is usually accomplished in two control levels. In the first level, usually called field level, the control system directly connected to the microgrid, the controller in this case should be able to accommodate the system to the environment. In the second manage level the control system ought to be automatically able to accomplish different system aims without external interference. [9]

In practice the control technology of microgrids may be realized by controlling the AC-coupling components of the microgrid. [7] These parallel operation principles and the droop control will be explained in the following chapters.

## 2.2 Control technology for the AC-coupling in microgrids

### 2.2.1 AC-coupling concept

The AC-coupling of the components of microgrids is a difficult task for the control technology. Nowadays, overwhelming majority of the systems operate in a mode where one device or process has control over one or more other devices the so-called "master/slave operation with one battery inverter or one genset as the grid master". [4] A big step in the development of distributed power supplies was achieved by introducing new concepts for hybrid systems with multi-master control that were demonstrated by ISET and SMA [8]. It was shown that parallel operation of inverters and small standard asynchronous and synchronous motors or generators inside one microgrid is possible. Multi-master control systems have high expandability but the system's design requires communication, supervisory control and extra cabling. It can be avoided if the components operate autonomously and instantaneously determine their active and reactive power set values. This concept has been realized by using reactive power/voltage and active power/frequency droops for the control of inverters [4]. These parallel operation principles and the droop control will be explained in the following chapters.

### 2.2.2 Voltage and frequency control during the parallel operation in high voltage grids

Voltage and frequency control concept was obtained from the active and reactive power equations. Power flowing into the line at point A, see figure 5, can be described with the following equation, where *P* is active power and *Q* is reactive power. [2]

$$\begin{gathered} P+jQ=S=U_1 I=U_1\left(\frac{U_1-U_2}{Z}\right)=U_1\left(\frac{U_1-U_2 e^{\mathrm{j}\delta}}{Ze^{-\mathrm{j}\Theta}}\right) \\ P+jQ=\frac{U_1^2}{Z}e^{\mathrm{j}\Theta}-\frac{U_1 U_2}{Z}e^{\mathrm{j}(\Theta+\delta)} \end{gathered} \tag{1}$$

Equation (1) can be divided into two equations, which separately express the values of the active and reactive power, see equations (2) and (3).

$$P = \frac{U_1^2}{Z}\cos\Theta - \frac{U_1U_2}{Z}\cos(\Theta+\delta) \tag{2}$$

$$Q = \frac{U_1^2}{Z}\sin\Theta - \frac{U_1U_2}{Z}\sin(\Theta+\delta) \tag{3}$$

Taking into account that $Ze^{j\Theta}=R+jX$ the equations (2) and (3) can be rewritten as:

$$P = \frac{U_1}{R^2+X^2}\left[R(U_1-U_2\cos\delta)+XU_2\sin\delta\right] \tag{4}$$

$$Q = \frac{U_1}{R^2+X^2}\left[-RU_2\sin\delta+X(U_1-U_2\cos\delta)\right] \tag{5}$$

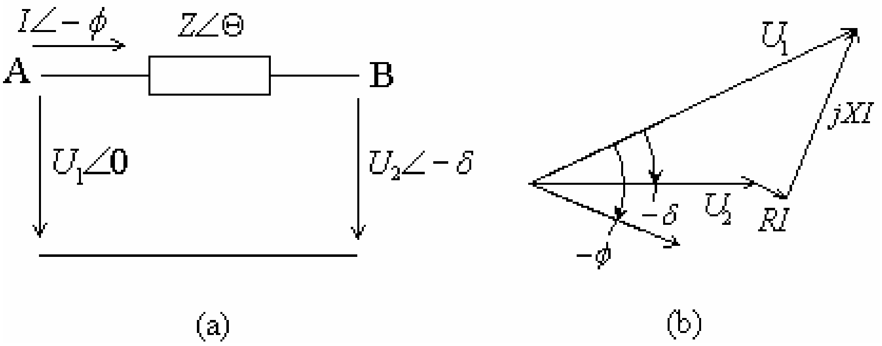

Figure 5. (a) Power flow through a line. (b) Phasor diagram. [2].

At first the voltage control in high voltage networks, e.g. transmission lines is described. In these networks reactance is much higher than resistance ($X$>>$R$), the resistance $R$ can be neglected ($R$ = 0). The power angle $\delta$ in these lines is small and we can assume that cos($\delta$) = 1 and sin($\delta$) = $\delta$. Taking into account these simplifications the equations (1) and (2) can be transformed to the equations (6) and (7). [2]

$$P = \frac{U_1}{X^2}XU_2\delta \tag{6}$$

$$Q = \frac{U_1}{X^2} X\left(U_1 - U_2 \cos\delta\right) \tag{7}$$

The equations (6) and (7) can be simplified to the following equations:

$$P = \frac{U_1 U_2}{X} \delta \tag{8}$$

$$Q = \frac{U_1^2}{X} - \frac{U_1 U_2}{X} \tag{9}$$

As we see the power angle is proportional to active power while the voltage difference $U_1 - U_2$ is proportional to the reactive power. The power angle can be controlled by the generator torque therefore the control of active power $P$ is realized by controlling the frequency setting in the power droop. In the same way, the control of the voltage $U$ is provided by controlling the reactive power $Q$. Such a way the voltage and frequency can be determined by using the active and reactive power values. This dependence can be expressed in the following equations, see equations (10) and (11). [18]

$$f - f_0 = -k_p (P - P_0) \tag{10}$$

$$U_1 - U_0 = -k_p (Q - Q_0) \tag{11}$$

Where $f_0$ and $U_0$ are the nominal frequency and voltage correspondingly. $P_0$ and $Q_0$ are the fixed active and reactive powers of the inverter. These reactive power/voltage and active power/frequency droops for the control of inverters call “Conventional droops”, see figure 6. [2]

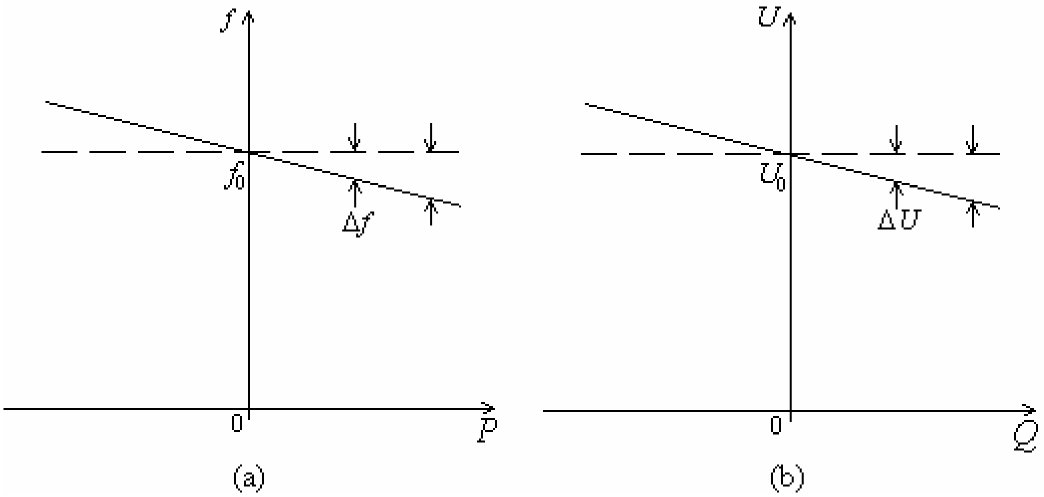

Figure 6. Frequency (a) and voltage (b) droop diagrams. Conventional droops. [4]

Using voltage and frequency control of the components allows remove expensive systems with control bus-bars from the microgrid and raise system efficiency. Droop control allows simple re-engineering of the system, simple maintenance and supervisory control. [4]

This presentation of the control method was represented for a virtual inverter model with *L* filter, see figure 7. Real inverter system usually comprises the *LC* or *LCL* filter. Such a real system with an *LCL* filter is shown in figure 8.

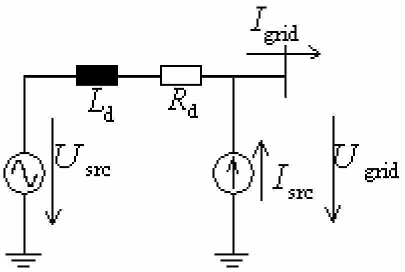

Figure 7. Virtual system model. [18]

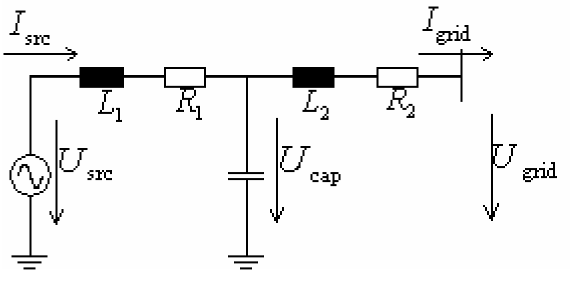

Figure 8. Real system model. [18]

Real inverter system should comprise the control scheme which would control the output voltage and current of the system independently from the external grid impedance’s changing. The output voltage and current should be equal to the output voltage and current of the virtual system. Such a control scheme which is able to realize voltage and frequency control in real systems is shown in figure 10. Voltage source generation block issues the signal $U_{src}$ taking into account the values of the amplitude and frequency of the capacitance voltage and the phase shift $\psi$ value which is calculated according to equation (12). Finite-output impedance emulation block calculates the required voltage value for the inverter in real system by using data from the virtual system voltage source, output voltage and output current. Such a way, using this control system in the inverters allows to emulate the virtual systems and to achieve the correct operating of the inverter irrespective of the main grid impedance.

$$\psi=-k_{\psi}(P-P_0) \tag{12}$$

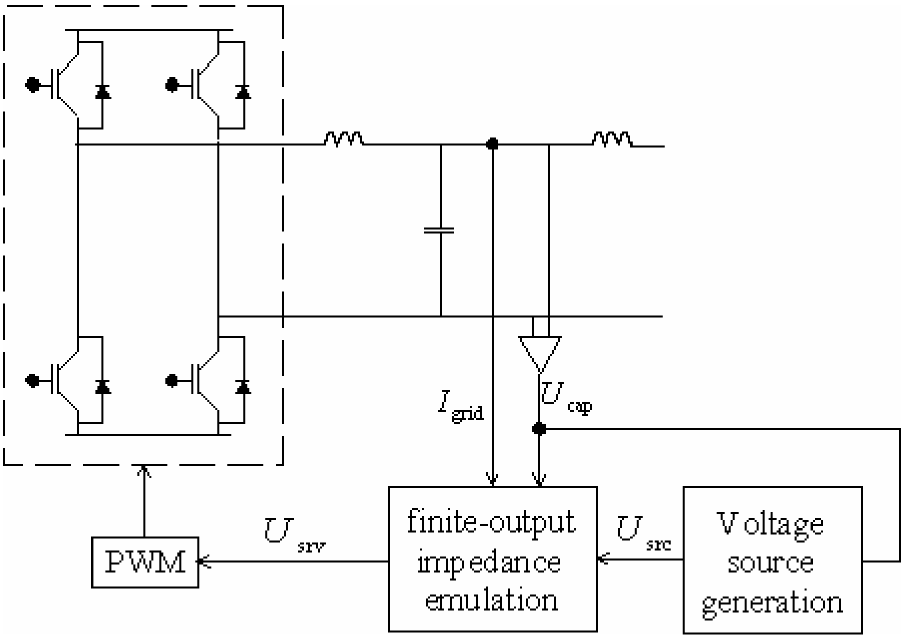

Figure 9. Scheme of the voltage and frequency droop control method. [18]

### 2.2.3 Voltage and frequency control during the parallel operation in low voltage grids

In low voltage distribution lines the active resistance is much higher than the reactance of the lines ($R >> X$) and therefore the voltage and frequency control principles are different compare to high voltage networks. By analogy with the high voltage networks reactance can be neglected ($X = 0$). The power angle $\delta$ is also small and we can assume that $\cos(\delta) = 1$ and $\sin(\delta) = \delta$. Taking into account these simplifications the active and reactive power expressed in the equations (1) and (2) can be written in the forms (13) and (14).

$$P = \frac{U_1}{R^2} R\left(U_1 - U_2 \cos\delta\right) \tag{13}$$

$$Q = \frac{U_1}{R^2}\left(-RU_2\delta\right) \tag{14}$$

The equations (13) and (14) can be easily simplified to the equations (15) and (16):

$$P = \frac{U_1^2}{R} - \frac{U_1 U_2}{R} \tag{15}$$

$$Q = -\frac{U_1 U_2}{R}\delta \tag{16}$$

It can be seen that in low voltage lines the voltage difference $U_1 - U_2$ depends mainly on active power while the power angle $\delta$ which represents frequency depends mainly on the reactive power. The control in low voltage networks is realized by the active power/voltage and reactive power/frequency droops, so-called opposite droops, see figure 10.

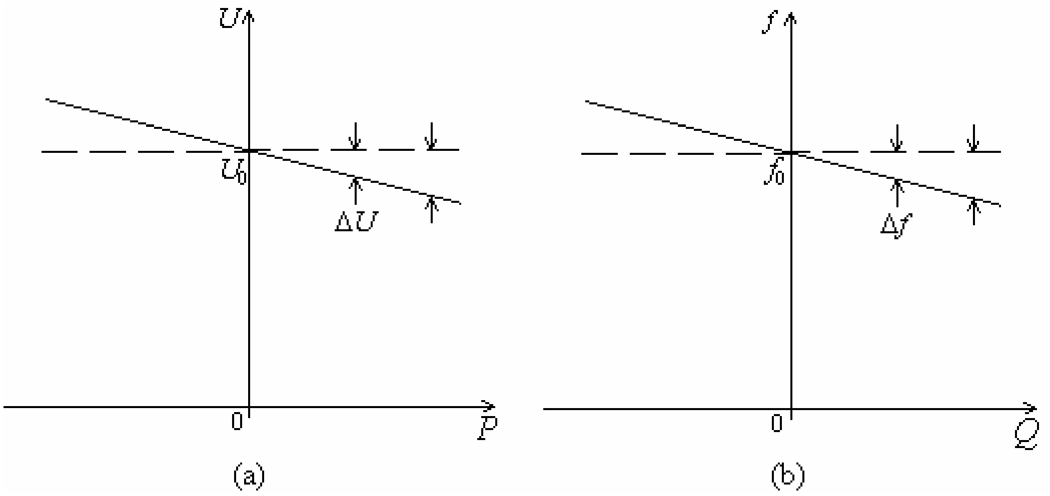

Figure 10. Voltage (a) and frequency (b) droop diagrams. Opposite droops. [12]

From the system's view the major control parameters of the low voltage systems are the voltage control and the active power dispatch, the following table gives a comparison of guaranteeing the major control parameters in conventional and opposite droop controls for the low voltage networks.

Table 2. Comparison of droop concepts for the low voltage level. [12]

| | conventional droop | opposite droop |
|---|---|---|
| compatible with HV-level | Yes | No |
| compatible with generators | Yes | No |
| direct voltage control | No | Yes |
| active power dispatch | Yes | No |

As we see from the table, opposite voltage control is suitable only for direct voltage control, but power dispatch in the control type is not possible. In case of opposite droop control system generators would supply only the nearest loads and voltage deviations would be present in the grid. Proceed from this the conventional droop control concept would be more suitable for control of low voltage grids if the direct voltage would be possible to be controlled. It is achieved on a property of the generators to change the voltage by means of changing the reactive power. The reactive power of each generator is adjusted in that way when the resulting voltage satisfies the desired active power level. In low voltage grids the reactive power depends on a frequency of the system. So, in that way the low voltage network can be regulated by active power/frequency droop control. [12]

## 2.3 Implementing of conventional droops in microsource control

### 2.3.1 Control methods.

It is obvious that implementing of conventional droops consist of using active power as a function of the frequency and reactive power as a function of the voltage. But it turned out, that in real micro systems it is easier to measure the instantaneous active power value. Therefore, it was proposed to use frequency as a function of the active power i.e. the voltage source inverter's (VSI) output power is used to adjust its output frequency. This control method was called "selfsync" and firstly was executed into the "Sunny Island" inverter by SMA Technologie AG. [7]

This control method is capable of providing unhindered connection of additional micro-sources at any point of the system and their operating without requiring information from the loads or other parts of the system. Each micro-source has a controller which responds to the system changes. The scheme of operating the micro-source controller is shown in figure 11. First three blocks provide instantaneous $P$, $U$, $Q$ values calculation. [7] Calculation of the reactive power beside the voltage and current values requires power factor control. Power factor value as written in chapter 2.2.2 can be calculated from equation (9). Required for inverter voltage magnitude and angle values are generated at separate $Q/E$ and $P/f$ droop blocks. Desired angle and voltage values are generated at the inverter blocks. The gate pulse generator produces correct short pulses according to which power electronic devices inside the inverter follow the control's claims.

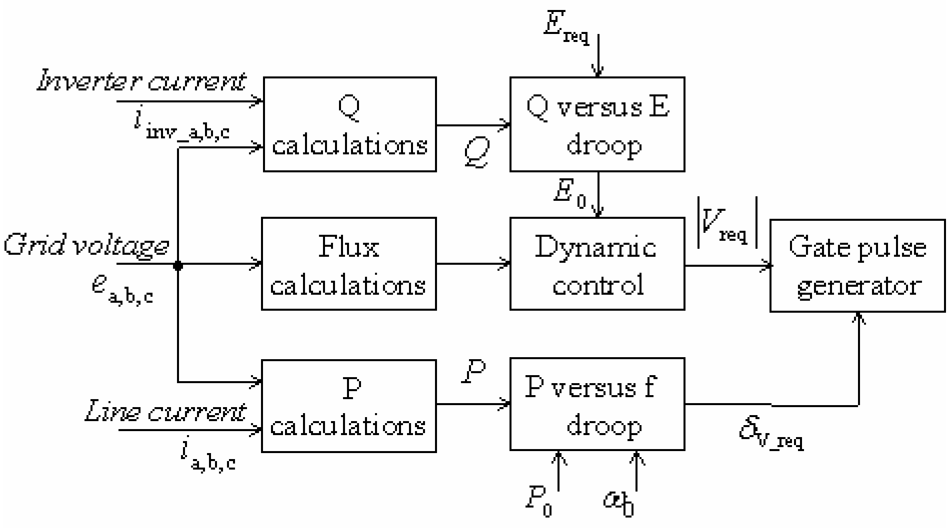

Figure 11. Microsource controller. [7]

Usually three basic manage configurations, which represented below, are used in microgrid's control.

- Unit power control configuration

Each distributed generation (DG) regulates its own voltage magnitude and supplied power. In this configuration each unit regulates to constant output power and in case of rising power level at any load extra power flows immediately from the main grid. During the island mode the power/frequency droop-control balancing power inside the island.

- Feeder follow control

The voltage magnitude is regulated by each DG at the connection points and at the same time DGs regulate the power at the points A, B, C and D, see figure 3. In this configuration the main grid provides a constant power supply to the microgrid and extra load consuming is picked up by the DG. In the case of the island operating mode feeder follow control configuration operating like a previous unit power control configuration when power balancing supported by the power/frequency droop control.

- Mixed control configuration

In this control manner one group of DGs regulates proper output power and another group regulates the supply power. But the units can control both supply and output power depending on the necessity. This configuration can offer the best operating mode when some units operate at peak efficiency and other units control the stability of the power flows from the main grid when the load conditions in the microgrid are changed. [7]

### 2.3.2 Power/frequency droop control

Unit power control configuration is realized by using the power/frequency droops. When a microgrid operates in the grid-connected mode loads may be supplied by the micro-sources of the microgrid and by the main grid. If the main grid suddenly cuts off the power supply, microgrid needs to transfer autonomously to the island method of operation. Regulating of the output power of the microsource is realized by controlling a negative slope of the line on the $P$, $\omega$ plane, see figure 12. The negative droop forms because when the power grows to $P_{\max}$ it is allowed for the angular frequency to drop by a certain amount $\Delta\omega$. The set points $P_{o1}$ and $P_{o2}$ usually called operating points determine the amount of power which injects from the corresponding micro-sources of microgrid connected to the main grid at the system frequency. In case of back transfer of the system – transfer to the island mode during the time when the microgrid imports power from the main grid – micro-generation needs to increase power to balance power inside the island. During this transfer system the frequency decreases and the operating points move to the lower frequency part of the line. Then sources increase their power output reaching the maximum power. If disconnection occurs during the time when microgrid exporting power to the main then the operating island frequency will be higher than the nominal frequency and the output power according to the diagram will decrease. The characteristics on the graph are the steady-state characteristics. [7]

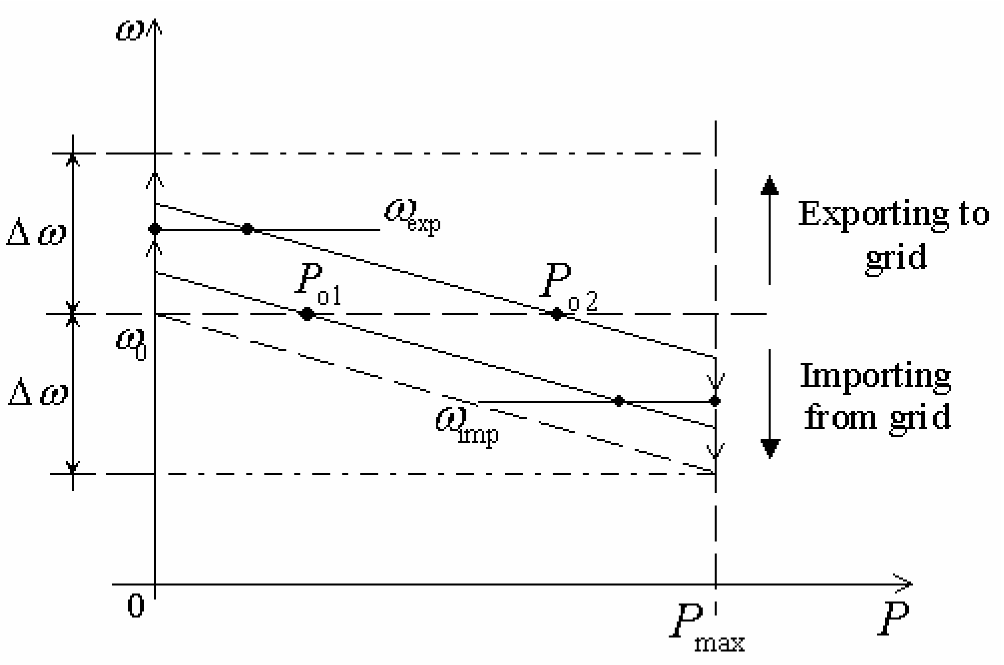

Figure 12. Active power vs. Frequency droop. [7]

### 2.3.3 Flow/frequency droop control

Feeder flow configuration is realized by using the flow/frequency droops. The magnitude of the flow is the same as in the power regulating graph but with another sign, and the main difference is that the location of the loads and sources in case of regulating of flow becomes important when in case of regulating power this factor is of significance. There are basic series and parallel configurations of the sources of the microgrid, see figure 13. Points $F_{01}$ and $F_{02}$ in figure 14 show the example of connecting two series connected units of microgrid when it is connected to the main grid. In point $F_{01}$ flow is negative that means the microgrid is exporting power to the grid. If the system transfers to island mode the flow reaches zero and the frequency grows up. In parallel configuration of the units the flow consists of the flows of each unit and can be obtained as a sum of the flows of the units. If the module of the flow $F_{02}$ is higher than the module of $F_{01}$ then the microgrid is demanding power from the main grid. In case of the equality of modules of the flows of the units the system lies in the island mode. [7]

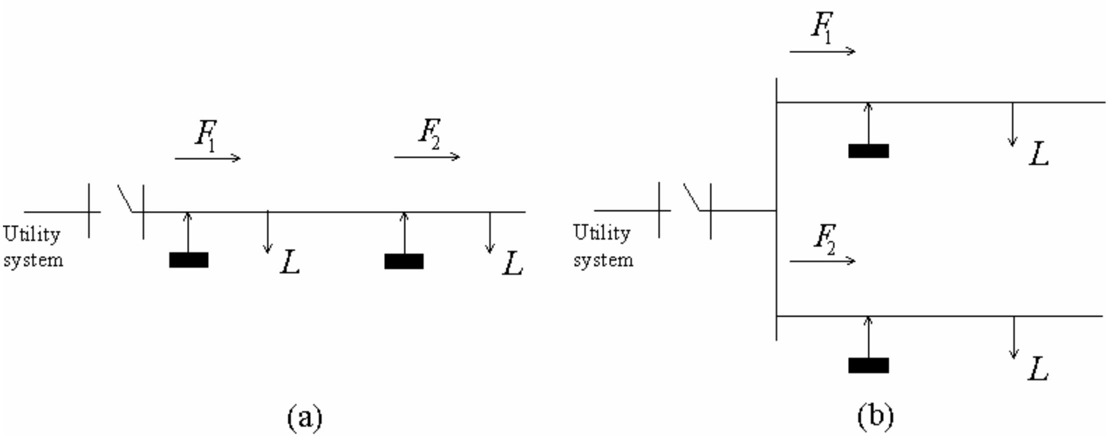

Figure 13. Series (a) and parallel (b) microgrid configurations with two sources. [7]

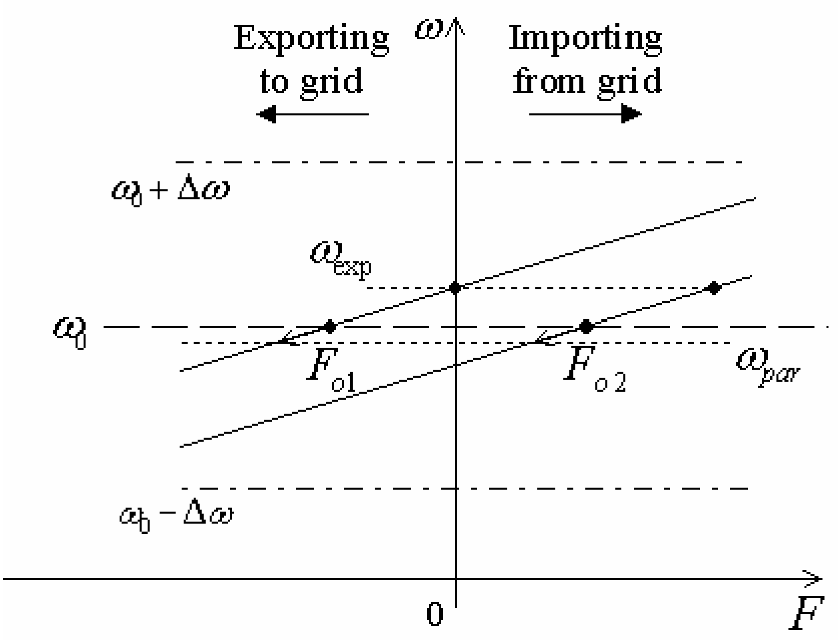

Figure 14. Feeder flow vs. Frequency droop. [7]

### 2.3.4 Voltage/reactive power droop control

In case of a large number of microsources local voltage control is required because a high number of the sources leads to voltage and reactive power oscillations and circulating of large reactive currents in the system. In that case implementing of the basic power factor control is insufficient. This requires implementing of voltage/reactive power droop controller, which reduces the local voltage at the set points when the reactive power generated by the micro-source will exceed the highest level. [7]

## 2.4 Control strategies for microgrid in islanded operation mode

Islanded operation of the system occurs unexpectedly and the microgrid should be able to react on this event. The control system of microgrid requires removing unbalance between the microsources and local loads of the microgrid. Disconnection from the utility grid ought to be very fast, therefore, disconnection transients of currents and voltages in the microgrid are very high. Microgrid control system should be able to reduce these transients also. Synchronous machines in the systems are able to provide demand and supply balancing in the system, but inverters should also be able to provide frequency control during islanded operation. Two main operation modes of the control system of microgrid during the islanded operation are possible: single master operation (SMO) and multi master operation (MMO)

1. Single Master Operation

Single master operation control strategy is shown in figure 15. The strategy principle is based on a master/slave operation principle. One of the inverters of the microgrid is the master inverter, inverter 1 in figure 15. It is used for the voltage reference when the main power supply disappears and for the operating with the battery bank, which is used in the microgrids for storing the excess of the energy from the micro-sources, see chapter 1.1. This inverter operates in the conventional droop mode under the control of its own control block, see figure 15. Control blocks of the inverters in the microgrids use information from the microgrid central controller (MGCC), which determines the generation profile of the microgrid for coordinated operating of the system. Inverter 2 is a slave inverter, see figure 15. This inverter operates in the conventional droop mode under the control of the droop control block, see figure 15. The droop control is realized by using the set point signals from the microsource controller (MC). The microsource controller (MC) generates signals based on the information from the microgrid central controller (MGCC) and sends it to the droop control block and to the microsource, see figure 15. More carefully, the principle of the operation of the microgrid central controller (MGCC) and microsource controller (MC) is described in chapter 2.1. The droop control method is described in chapters 2.2 and 2.3. Such a way the system operates and feeds the loads even when the power supply from the electrical network disappears.

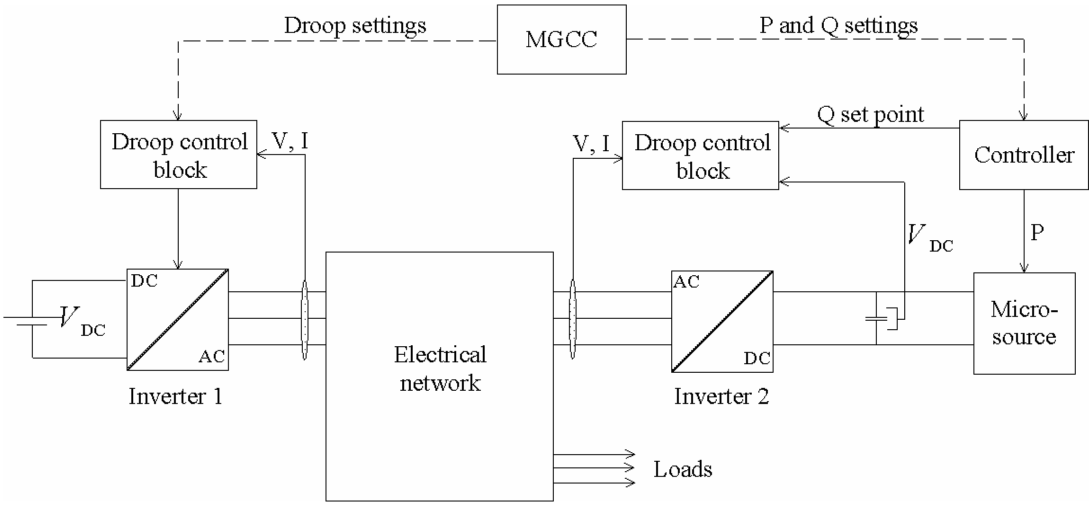

Figure 15. Control scheme for Single Master Operation. [3]

2. Multi Master Operation

Multi master operation principle assumes the case when more than one inverters are operated as a master, inverters 1 and 3 in figure 16. These inverters operate like in the single master operation in the conventional droop mode under the control of its own control blocks. Master inverters in the multi master operation mode can be connected to the storage devices or to the microsources. Slave inverters are also presented in the multi master operation, inverter 2 in figure 16. Generation profiles of the microgrid in this case are also determined by the MGCC. They can be modified by changing the frequency of the master inverters or by controlling the output power of the microsources. An overview of this control strategy is shown in figure 16. [3]

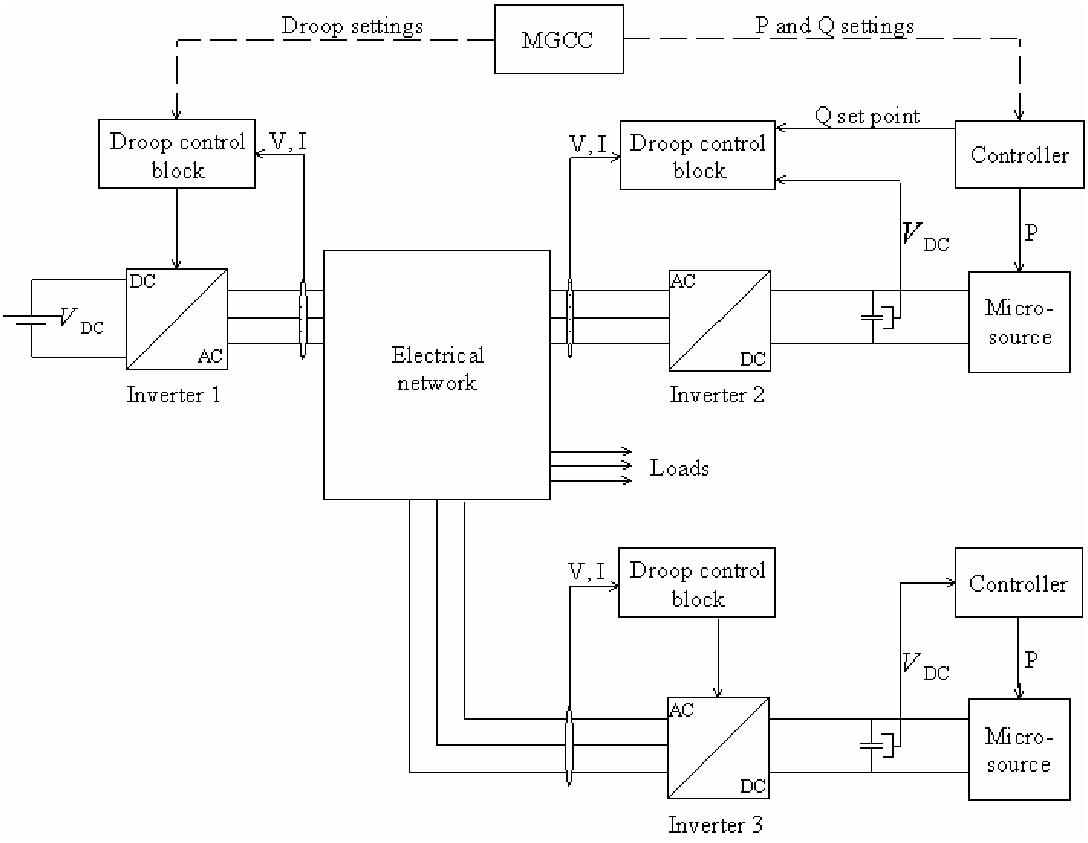

Figure 16. Control scheme for Multi Master Operation. [3]

## 2.5 Three phase parallel operation

Single phase inverters can be applied for three phase parallel applications by integration of three inverters to one “three phase cluster inverter” [4]. Figure 17 shortly depicts the structure of that three phase cluster inverter system. There are three single phase inverters connected to common battery. One of the inverters is called “droop master” [4], the inverter L1 in figure 17. This inverter is responsible for the operation of the cluster. “Droop master” inverter operates in the droop control mode, which is described in this thesis in chapters 2.2 and 2.3. The internal bus is used for the communication between the “droop master” inverter and two slave inverters, the inverters L2 and L3 in figure 17. This bus is needed for transferring the required information for the correct operation of the cluster. Start/stop signals, measured battery current and AC power values are transferred by the internal bus. In addition for the correct operation of the cluster the phase shift control between the phases is required to be. Extra communication wires, see “Sync. signal” wires in figure 17, are used for realizing this control. “Droop master” inverter L1 sends the signal via this synchronization wires to the inverters L2 and L3. This synchronization signal is sent at the beginning of each cycle of the sine wave of the L1 inverter's AC-voltage. Slave inverters at that time calculate their frequency and AC-voltage taking into account the phase shift ±120°. Such a way three phase supplying is realized in the microgrids by using the theory of the droop control. [4]

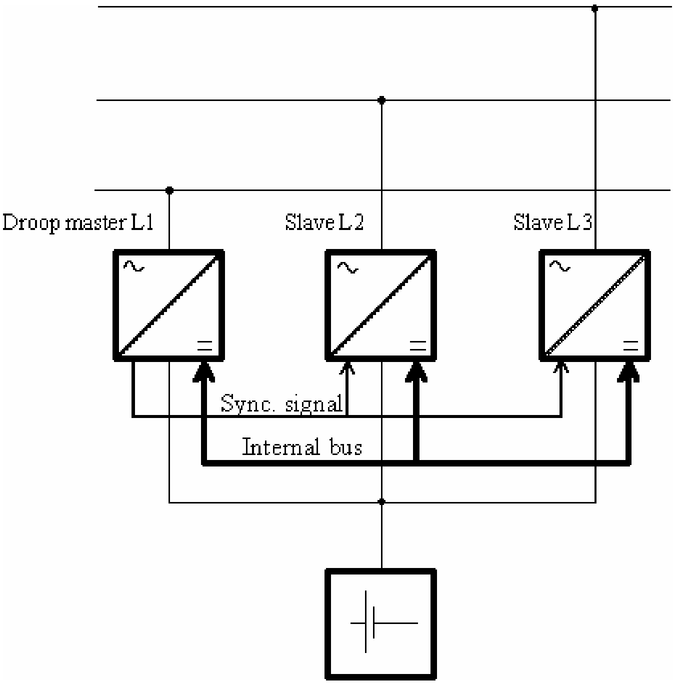

Figure 17. "Three phase cluster inverter". [4]

## 3 Protection of microgrids

Protection system in microgrids is required to operate in both interconnection and isolated operating modes. In case of fault on the main grid's side during the interconnecting operating mode, it is required to isolate the microgrid from the grid as fast as possible to protect the microgrid loads. And in case of fault inside the microgrid it is required to isolate the faulted part of the system. [1]

Due to these reasons two main questions appear during the developing process of each microgrid: when microgrid should be disconnected from the utility grid if the main grid operates unstable and how to divide microgrid on a segments which can successfully operate separately in case of damage of any of them.

The protection systems of microgrids are short circuit based. In other words in microgrid protection systems usual protective devices are used. Among them are the fuses, circuit-breakers and over-current definite devices. The distribution protection is based on a short-circuit current sensing. [1] The protection system must sharply define the boundary between an abnormal and normal operating modes of the utility grid. The speed of isolation is dependent on the specific properties of the microgrid's loads. An appropriate circuit-breaker should be installed at the point of common coupling (PCC), see chapter 1.5. But some customers need the specific protection systems. Microsources which are based on power electronic devices cannot provide the required level of short circuit current. Some power electronic devices cannot react on to high level of overcurrent. In these cases the microgrid should be disconnected from the main grid during the time less than 50 milliseconds after an abnormal mode in the network is started. It is impossible to achieve such high speed of the operating of the protection system with usual circuit-breakers, in this case the unique nature of the microgrid design requires new approaches in relaying design. For the protection of the microgrids usually differential protection system or zero sequence voltage relays are used or a very fast disconnecting transfer trip system must be installed between the circuit-breaker and the main grid [19]. At the same time, since very high speed disconnections are carried out, high amplitude currents are appeared. Due to this, proper grounding of microgrids must be provided. Also the protection system which operates with the microgrid in the island mode must distinguish the fault currents from the maximum load currents when the microgrid operates in the grid-connected mode, because these currents can also be very high. [19] When the fault occurs inside the microgrid during the interconnected operating mode, protection system must isolate the smallest possible section around the faulted part of the microgrid to eliminate the fault. In case of fault during the isolated operating mode protection system is required to isolate the fault, micro generators and other units of the microgrid. [1]

Typical microgrid's protection system configuration is shown in figure 18. The picture depicts additional protection and communication channels. It also shows the disposition of the controllers and coordinators of the protection system and the circuit-breakers' arrangement. [19]

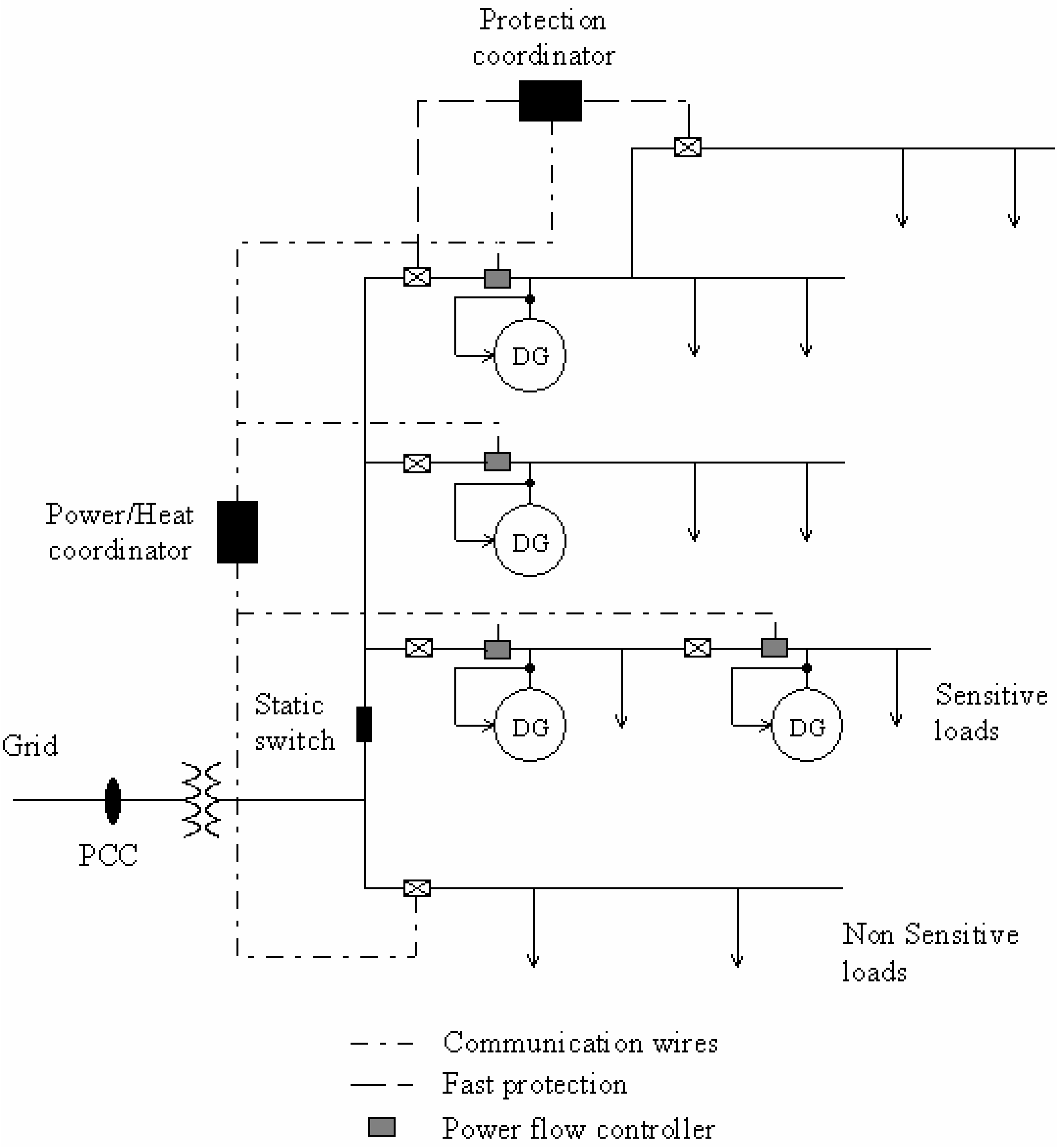

Figure 18. Typical microgrid protection concept. [19]

# 4 Microgrid test setup in laboratory

## 4.1 Tested equipment

Two models of inverters are tested during the research. Among them are “Sunny Island 3324” bidirectional power converter and “Hydro Boy 1124-50C” inverter for supplementary grid feeding designed by SMA Technologie AG. Master inverter in built microgrid is “Sunny Island 3324”. “Hydro Boy 1124-50C” is a slave.

The large role of the inverter is to regulate the voltage and frequency of the system during the island operation mode by controlling the active and reactive power. It means that the battery inverter operating as a grid forming unit during the island mode. When the microgrid operates in parallel with the main grid, the inverter is acting as a grid following unit. The aim of the research is to set up a test microgrid based on these inverters, to test this microgrid and to estimate different operating modes of the inverters and the whole grid.

The “Sunny Island 3324” is a bidirectional power converter. This means that it operates like a battery inverter in one direction and like a battery charger using power sources from the AC side in opposite direction. Energy sources and loads can be connected to the “Sunny Island 3324” in both AC and DC sides. This inverter is able to connect the utility grid or start automatically the AC generator, which can be used instead of the main grid, in accordance with microgrid’s requests. “Sunny Island 3324” also has a system which protects the battery bank from incorrect charging and deep discharge. The “Sunny Island 3324” inverter which operates with the battery bank is responsible for the proper handling of the batteries to ensure their long life.

The power sections of the “Sunny Island 3324” one-phase battery inverter is depicted in figure 19. It is a bidirectional device and allows charging and discharging of the batteries. Eight four-quadrant DC/AC converter comprise single phase IGBT bridges. System also comprises standard EMI filter and grid-connection transformer, see figure 19.

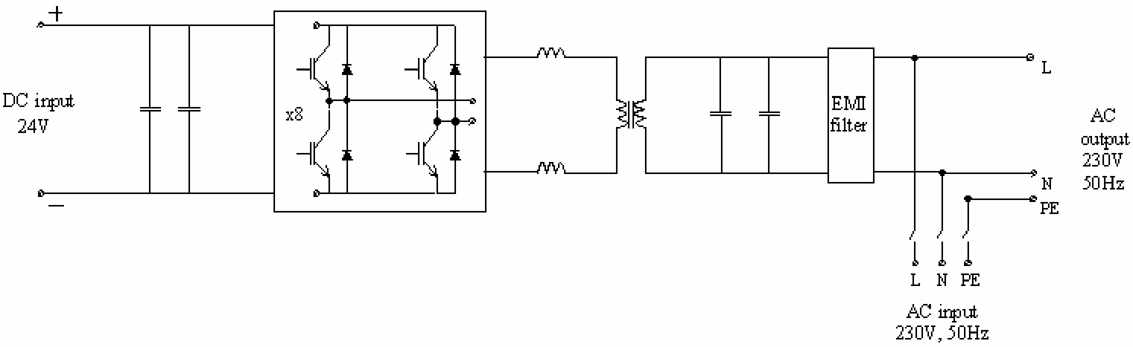

Figure 19. Power section of the “Sunny Island 3324” battery inverter. [6]

SMA inverter operates by regulating the magnitude and the frequency of the output voltage the so-called voltage control mode. Inverter’s aim is to form the grid when it operates in island mode and to communicate with the utility grid to maintain operating frequency and voltage of the system. [6]

“Hydro Boy 1124-50C” SMA Technologie AG one-phase battery inverter is used for grid feeding with AC voltage by conversion the DC voltage of the fuel cells. The scheme of the inverter, see figure 20 includes a MOSFET bridge and a toroidal core transformer. DC voltage from fuel cells with approximate frequency 16 kHz is supplied to this inverter and conformed output 230V AC voltage which is fed into the grid. [15]

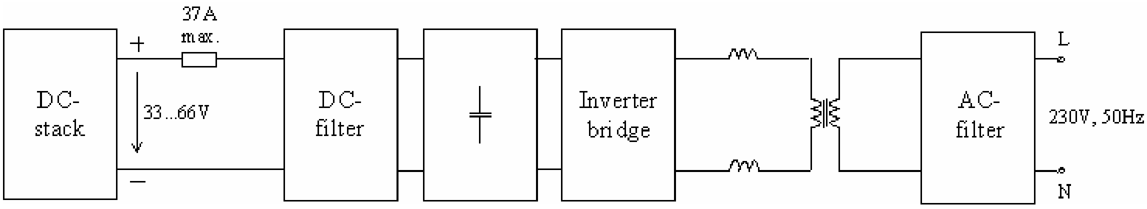

Figure 20. Principle scheme of the Hydro Boy. [15]

## 4.2 Composition of microgrid system in laboratory

The composition of one-phase microgrid system based on SMA Technologie AG inverters in laboratory is shown in figure 21. The system comprises a DC generator with nominal power of 1200W and maximum DC current of 37A. The generator is used as the primary power source which emulates the work of a fuel cell generator, this generator is interfaced to the 1-phase AC bus against DC/AC PWM “Hydro Boy 1124-50C” inverter and feed local load. The voltage of the AC side of the “Hydro Boy 1124-50C” is 209...251V at the frequency 49...51Hz. Also system comprises the battery bank to insure continuous supply of the local load. Battery capacity is required to be 100 … 6000 Ah, charging current and voltage level is about 104 A and 24 V correspondingly.

The system envisages connection of the utility grid with supply voltage 230V at the frequency 50Hz. The main grid is interfaced to the microgrid via “Sunny Island 3324”, which provides distribution of the energy in the system. The network feeds microgrid when the internal sources of the microgrid are not managed with the load’s feeding.

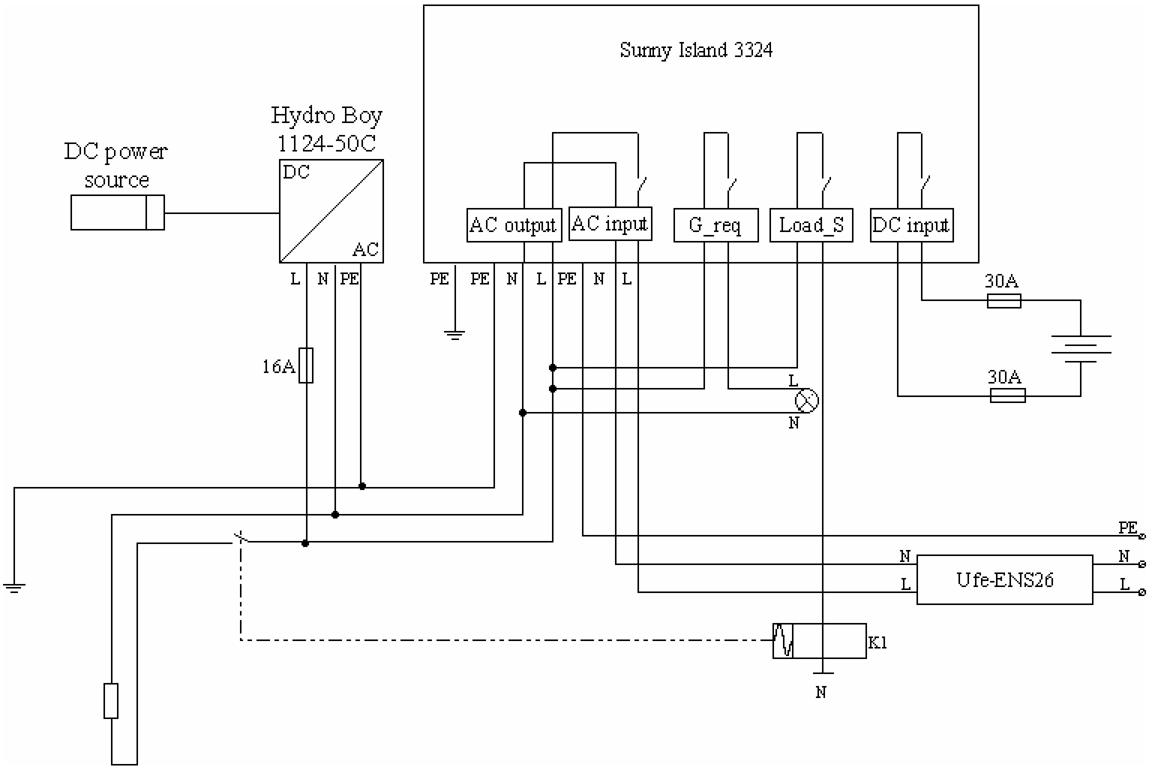

Figure 21. Laboratory microgrid setup.

## 4.3 Laboratory microgrid control

The control of the microgrid is provided by the “Sunny Island 3324” inverter. A DC power source, which emulates a fuel cell system, as written in chapter 4.2, supplies the local load. If the power consumption exceeds the amount of the energy which is generated by the DC generator, additional power from the battery bank is fed to the local load. In other cases the battery is charged by the excess energy. The battery bank is one of the most expensive and unsafe components of the microgrid. It is required to avoid battery bank full discharge during the exploitation period. The Sunny Island inverter envisages critical battery discharge mode. There are three battery protection levels in the “Sunny Island 3324” inverter. When the battery achieved the first critical state, “Sunny Island 3324” connects the main grid and feeds the energy to the battery bank. In built microgrid this connection is realized manually. “Generator control relay” (G_req), see figure 21, of the “Sunny Island” is connected to the 12 V control light when the battery bank achieves the critical state, control signal feeds control light to inform the user that the battery needs to be charged. Then the user should manually connect the utility grid. If the batteries still discharge and the second fixed critical level is achieved “Sunny Island 3324” load shedding relay (Load_S) switches and disconnects the loads, see figure 21. If it is not done for some reasons and batteries further discharge the inverter automatically switches to the standby mode to avoid further discharging of the batteries. [16]

### 4.4 Features of the laboratory microgrid protection

All connections between components of the microgrid are protected by fuses, protecting relays and circuit breakers. To protect battery bank two NH1 30A fuses are used. Connection between the DC generator and the local load is protected by a 16A automatic circuit beaker. The connection between the microgrid and the utility grid requires to be protected by the automatic switching unit. In laboratory setup Ufe-ENS26 automatic isolation unit is used for that protection. This independent unit monitors feeding system and protects microgrid from over voltage and under voltage, frequency deviations and impedance jumps of the main grid.

## 5 Tests of the setup.

During the tests currents and voltages in different parts of the microgrid were measured using Fluke 199 oscilloscope. Actual active power and power factor of the load were obtained using Norma wattmeter D 1150. Also in some tests the internal measuring equipment of the inverters was used. All measured data was registered by a personal computer and processed using MATLAB 7.0. Program code for MATLAB can be seen in Appendix A.

The objects of the tests are to investigate all main modes and parameters of the microgrid, to evaluate the electricity quality and reliability of supplying power from the microgrid to verify the control strategies of the microgrid. Also the aims of the tests are to verify the main components of the microgrid - the inverters and to investigate the transition operating modes of the microgrid, when the microgrid converts from the grid connected mode to the islanded operation and backwards.

## 5.1 Test 1. Fourier analysis of the microgrid output current and voltage. Inductive load.

During test 1 the system operated in the islanded mode. The aim of the test is to evaluate current and voltage waveforms and corresponding spectra during the different operation modes of the microgrid. A very inductive load was connected to the microgrid during the first part of the test which is described in the following chapters. During the first test the system operates in islanded mode.

### 5.1.1 Hydro Boy feeding

Three fans and one motor were used as a load. The parameters of the load are presented in table 3.

Table 3. Load parameters

| | |
|---|---|
| Active power. *P*(W) | 438 |
| cos(*φ*) | 0.51 |
| Total apparent power (calculated) *S*(VA) | 859 |

During the test all power comes from the Hydro Boy[1]. A small excess of generated power by the DC source flows to the battery. The battery DC current equals 1A DC. The following figures depict the current and voltage waveforms at different parts of the system during this test.

As seen in table 3 the load which consists of three fans and a motor in this test is really inductive. The power factor of the load is equal to cos(*φ*) = 0.51 ind. The load current is non-linear, see figure 22. The Sunny Island[2] current at the AC side is also really non-sinusoidal, see figure 26. But at the same time the load voltage is sinusoidal, see figure 24. A few questions appeared during the carrying out of this test. Is the load

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[1] In this thesis, term “Hydro Boy” will be used for the “Hydro Boy 1124-50C” inverter which is described in chapter 4.1

[2] In this thesis, term “Sunny Island” will be used for the “Sunny Island 3324” inverter which is described in chapter 4.1

really non-linear or does the Hydro Boy give disturbances to the system? Why Sunny Island's current is so distorted? Does the Sunny Island try to maintain the sinusoidal load voltage?

To understand how the Hydro Boy and Sunny Island inverters influence on an output power of the system the following tests were carried out, see chapters 5.1.2, 5.1.3 and 5.1.4.

During the test realized in this chapter also the current at the DC Sunny Island side was measured, see figure 28. The current at the DC Sunny Island side is really non-linear. It is connected to the presence of the really inductive load at the system during this test which defines the high level of reactive power in the system. A big amount of the reactive power is going through the Sunny Island. Therefore the Sunny Island must transfer a large amount of current between the battery and the load. Then if the DC-link capacitors in the Sunny Island are too small to reserve this energy in its DC-link it has to transfer energy from and to the battery in order to keep the DC-linkage voltage in its allowed limits. Then, such big a current ripple at the DC side of the Sunny Island is observed.

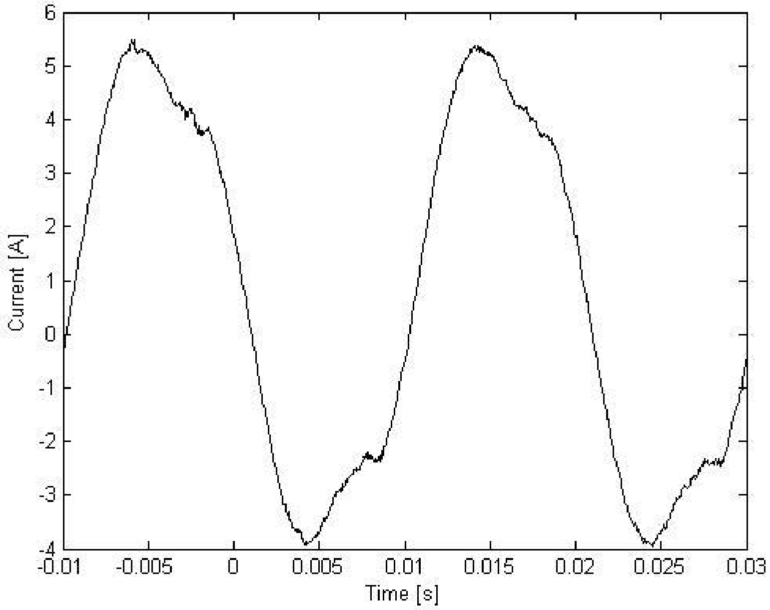


Figure 22. Load current.

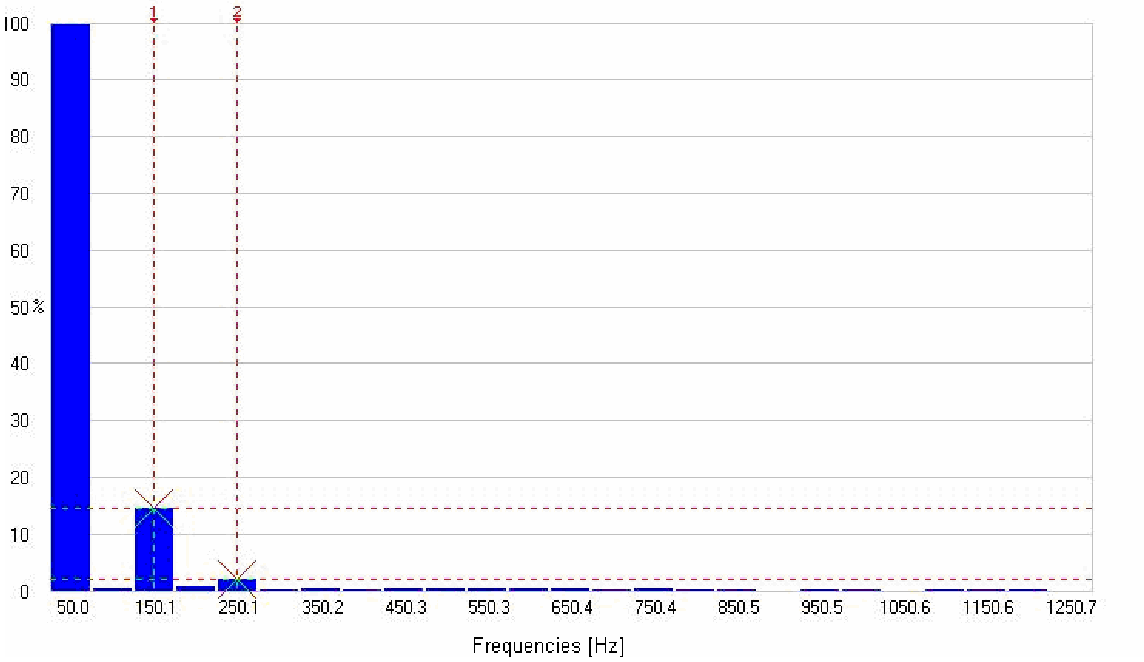


Figure 23. Load current spectrum. 3rd harmonic is 14.7%. 5th harmonic is 2.2%.

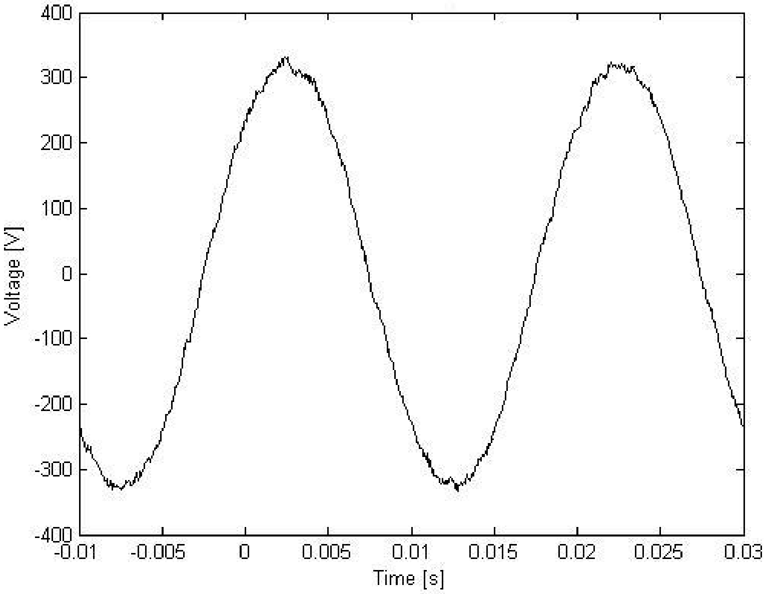


Figure 24. Load voltage.

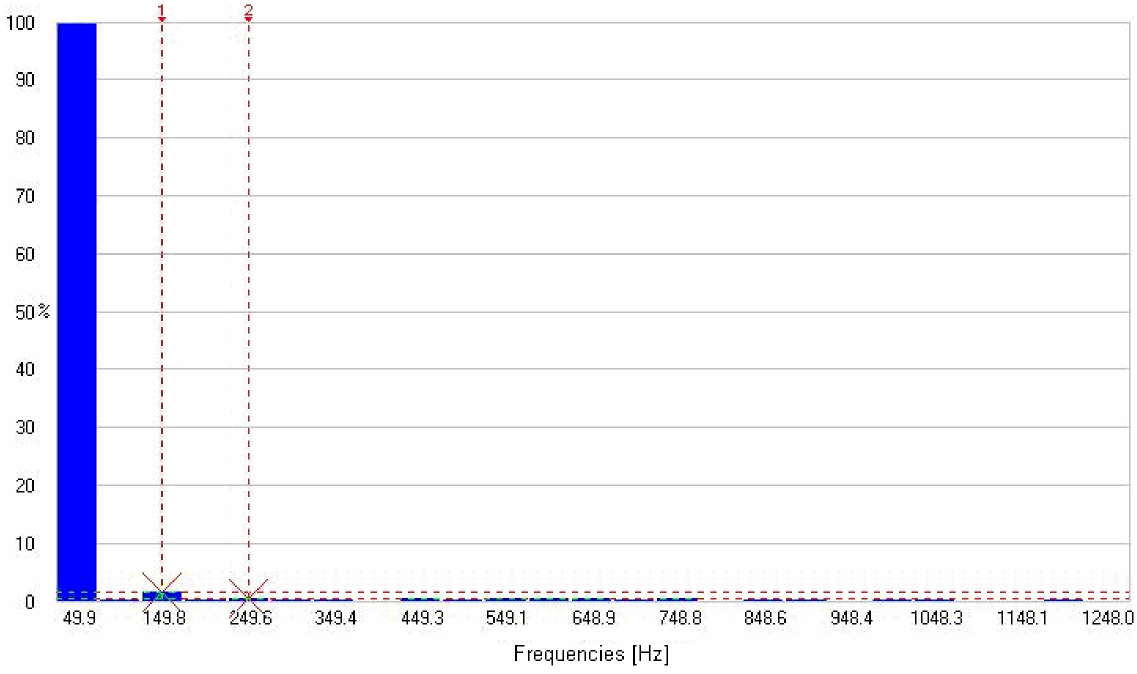


Figure 25. Load voltage spectrum. 3rd harmonic is 1.7%. 5th harmonic is 0.5%.

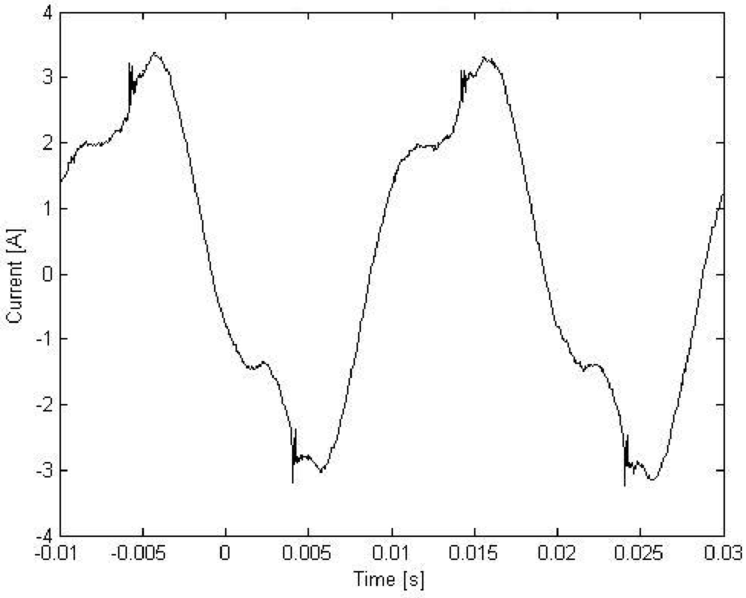


Figure 26. Sunny Island current (AC output).

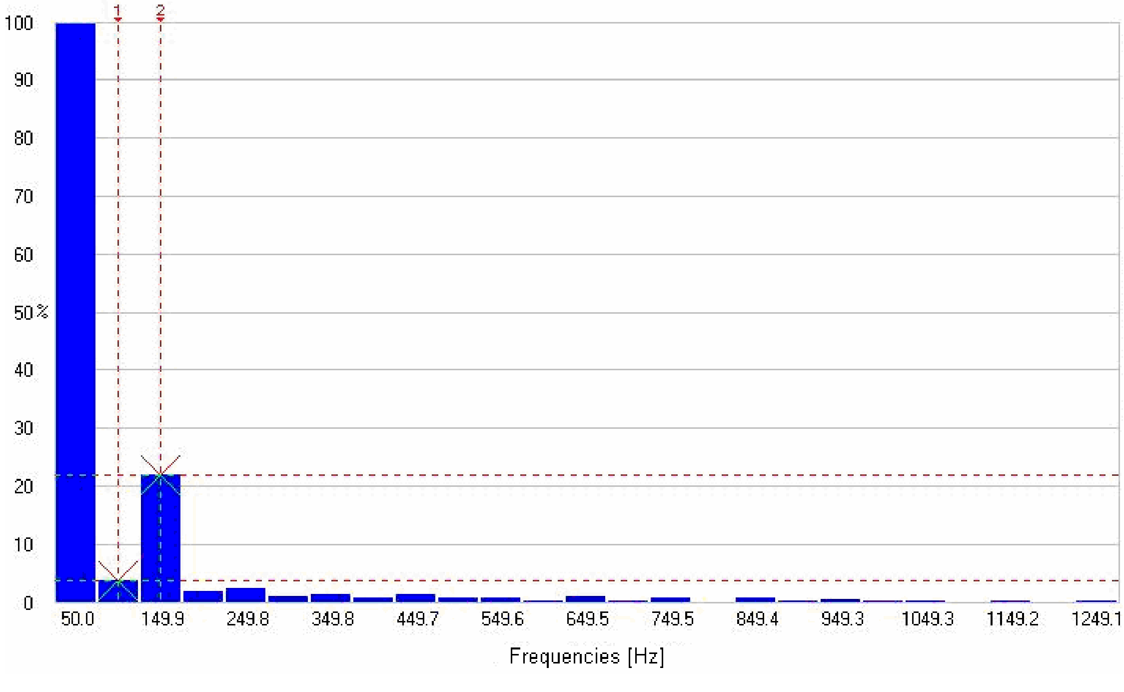


Figure 27 Sunny Island output current spectrum. 2nd harmonic is 3.9%. 3rd harmonic is 21.9%.

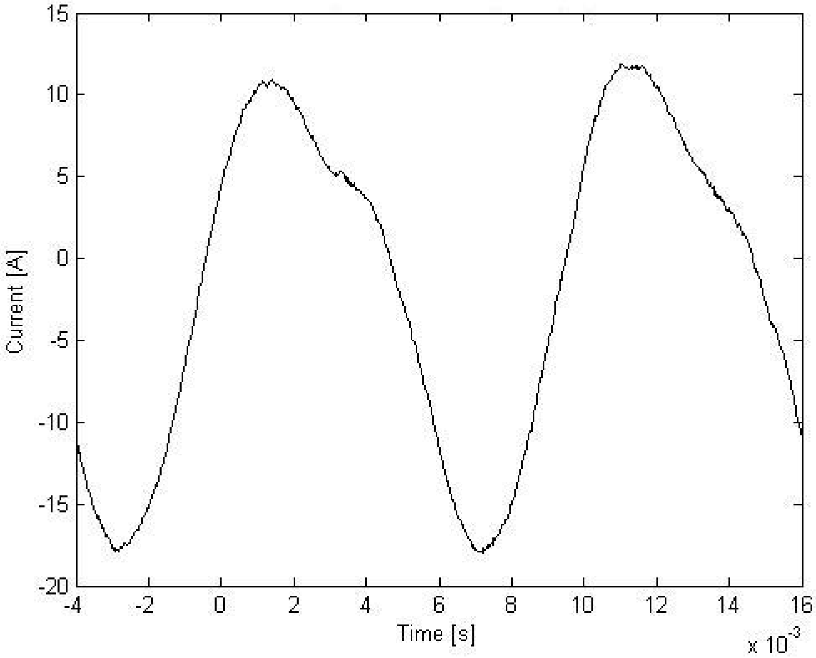


Figure 28. Sunny Island current (DC input).

### 5.1.2 Hydro boy regulated microgrid

Second part of the first test assumes the same test with the same load which consists of three fans and a motor as in the first case, parameters of the load are presented in table 3, but the output of the Hydro Boy in this case is connected to the main grid and the input of the Hydro Boy is connected to the battery bank, which emulates the fuel cell generator. Such a way a microgrid regulated by the Hydro Boy with the battery DC source and with the utility grid at the AC side was made. It was made to investigate the microgrid when on/off inverter - Hydro Boy controls the system and feeds the loads.

The main grid was connected to the output of the Hydro Boy because it is required to connect the Hydro Boy AC output to the main grid or to the master inverter because the Hydro Boy sends the synchronization impulses and tests the system before starting the operation, if there is no voltage at the AC side of the Hydro Boy, it would not operate. In this test the grid current, see figures 33 and 34, is better than the Sunny Island AC output current in the previous test, see figures 26 and 27. The load current waveform in the test of chapter 5.1.1 with the system which was managed by the Sunny Island, see figures 22 and 23, is better than the current waveform in this test, where the system was operated without Sunny Island, see figures 29 and 30. Proceed from this we can make a conclusion that the Sunny Island is trying to compensate the disturbances of the system and maintain the sinusoidal voltage by supplying harmonics to the system.

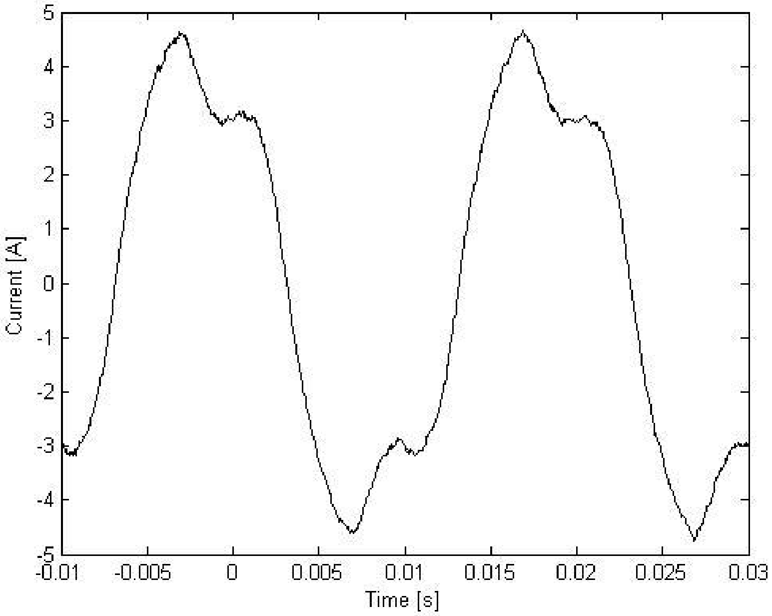


Figure 29. Load current

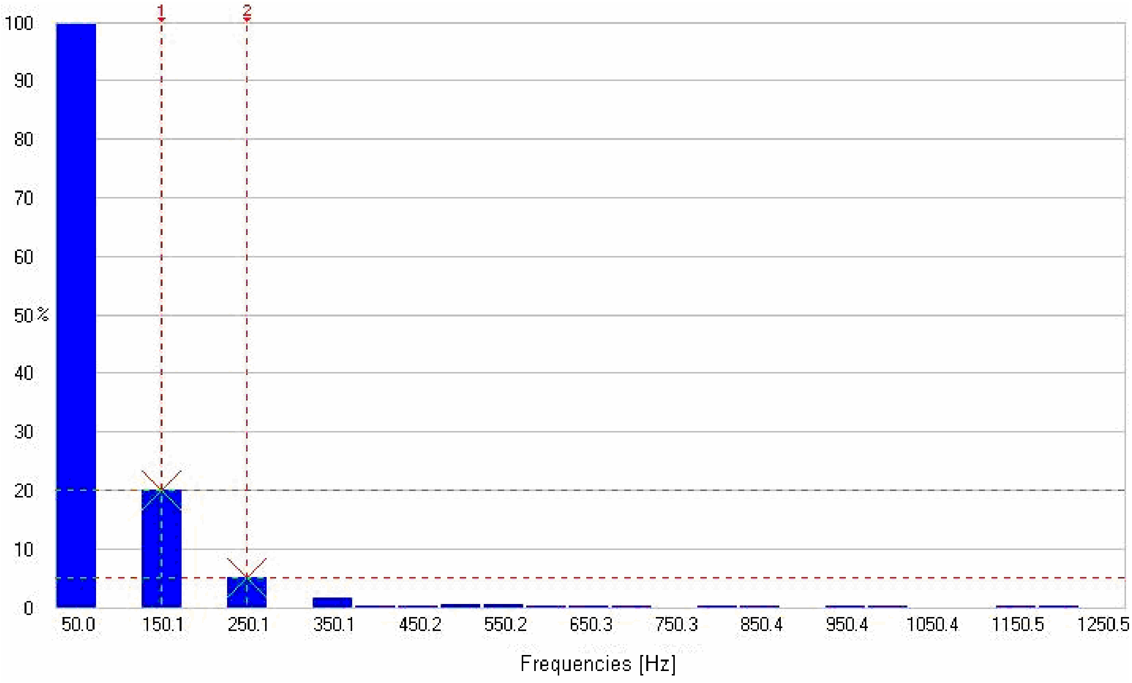


Figure 30. Load current spectrum. 3rd harmonic is 20.1%. 5th harmonic is 5.3%

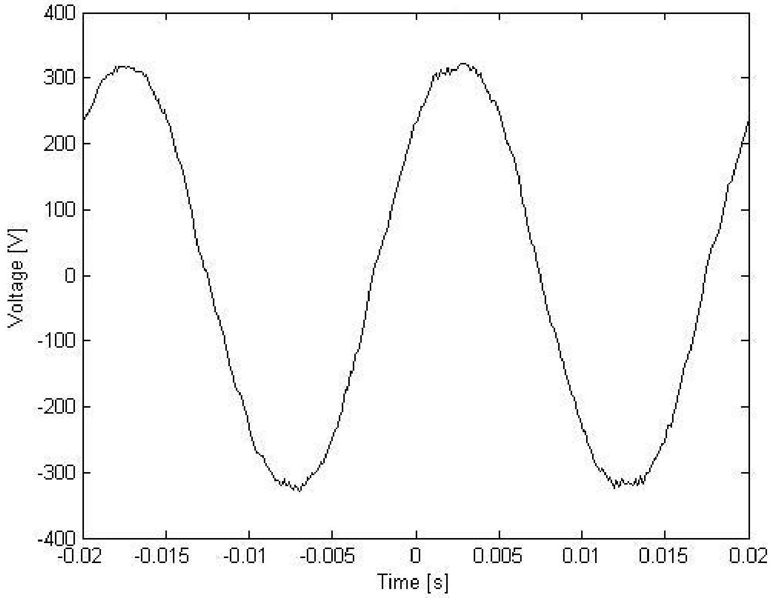


Figure 31. Load voltage

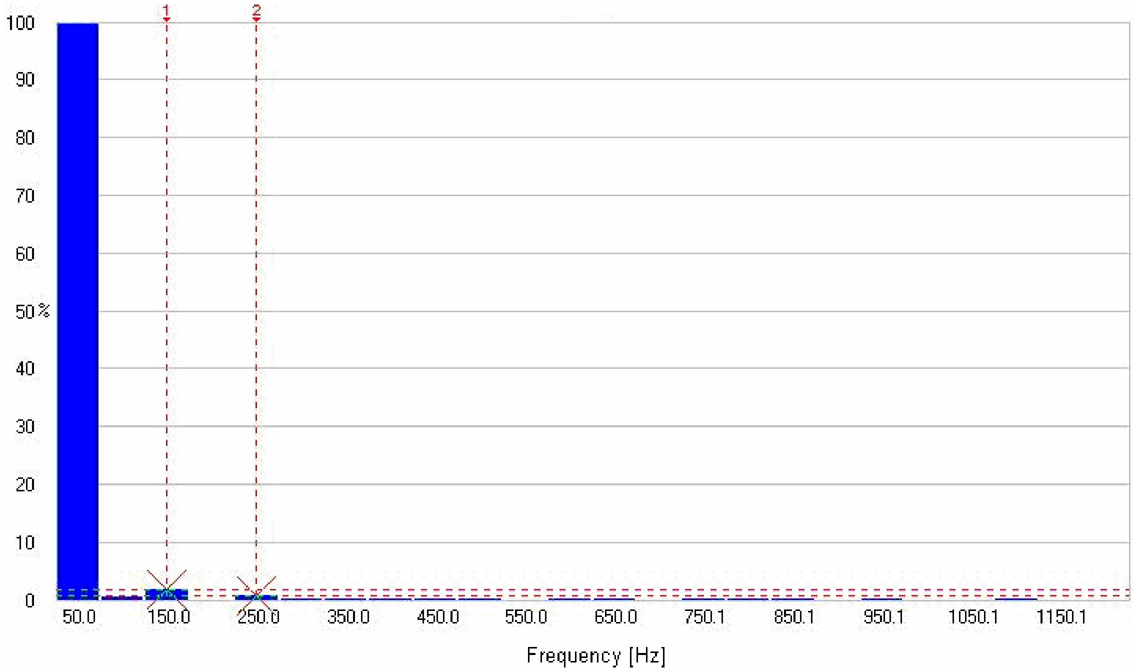


Figure 32. Load voltage spectrum. 3rd harmonic is 1.5%. 5th harmonic is 0.5%

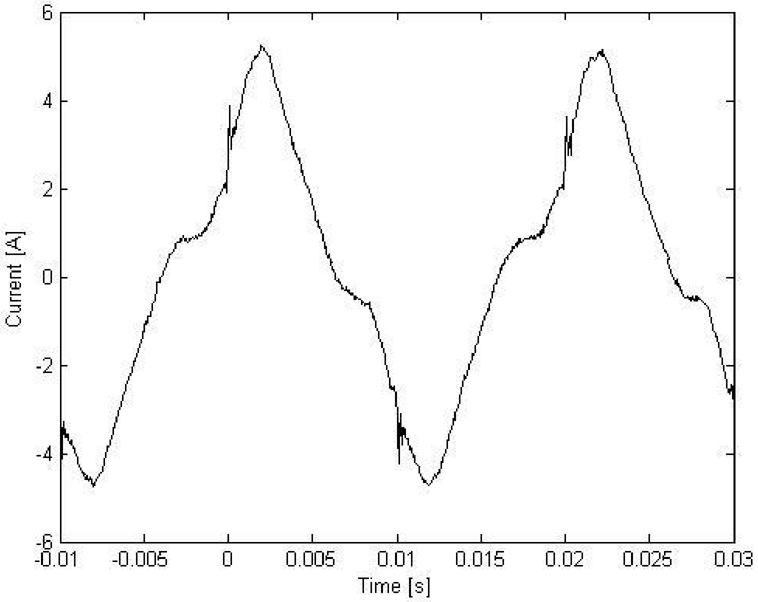


Figure 33. Grid current

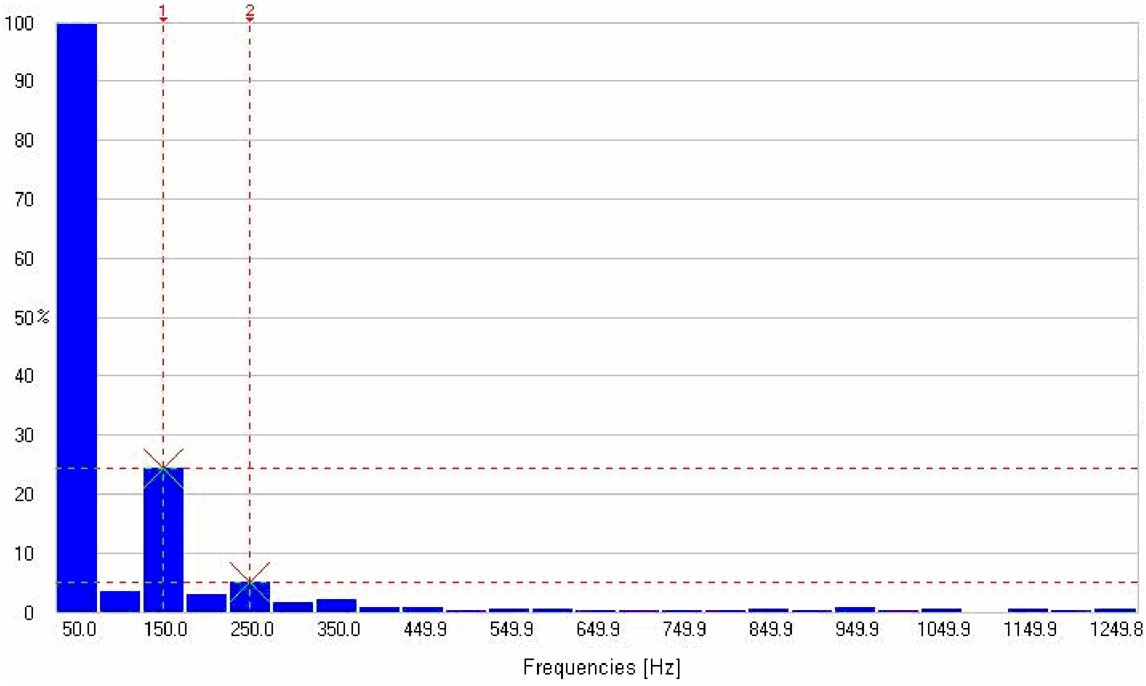


Figure 34. Grid current spectrum. 3rd harmonic is 24.4%. 5th harmonic is 5%

### 5.1.3 Sunny island feeding

During the third part of the first test the Sunny Island inverter was tested. Hydro Boy was off and the same load, see table 3, supplied by the battery bank using the Sunny Island. The current and voltage waveforms and the corresponding spectra were obtained, see the following figures.

The load current and voltage in this test, see figures 35 and 37 where the Hydro Boy is disconnected from the system and the load current and voltage in the test of chapter 5.1.1 where the load is fed from the Hydro Boy, see figures 24 and 26 are different. This difference is also seen in the figures of spectrum of these currents and voltages, figures 36 and 38 and figures 25 and 27 correspondingly. This proves the statement that the Hydro Boy gives disturbances to the system.

The current at the DC Sunny Island side in this test is also really non-linear, see figure 39, like in the test of chapter 5.1.1. It is connected with really inductive load, see load parameters in table 3. As it was mentioned earlier, in chapter 5.1.2, the Sunny Island is trying to keep sinusoidal load voltage. This can be done by controlling the reactive power flows. The Sunny Island must transfer a large amount of current between the battery and the load. Then if the DC-link capacitors in the Sunny Island are too small to reserve this energy in its DC-link it has to transfer energy from and to the battery in order to keep the DC-linkage voltage in its allowed limits. Then, such big current ripples at the DC side of the Sunny Island are observed.

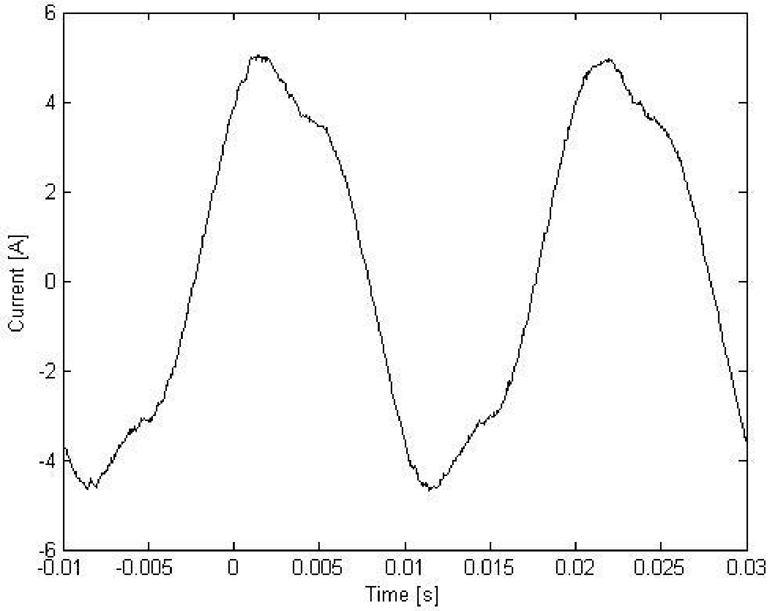


Figure 35. Load current

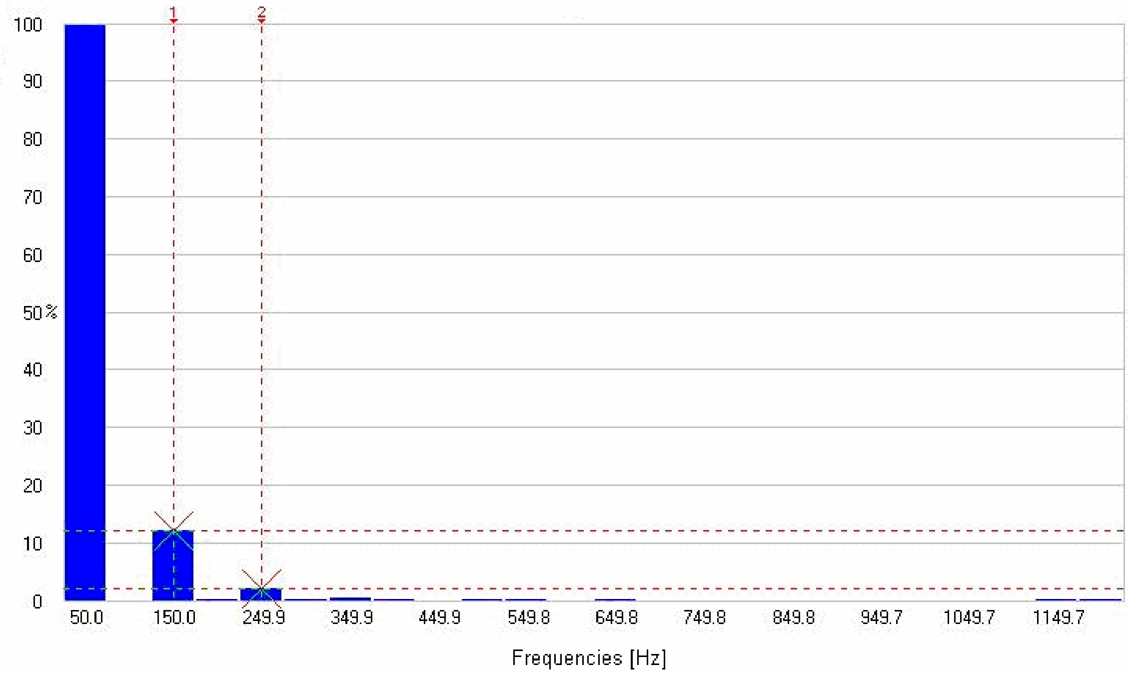


Figure 36. Load current spectrum. 3rd harmonic is 12.3%. 5th harmonic is 2.2%

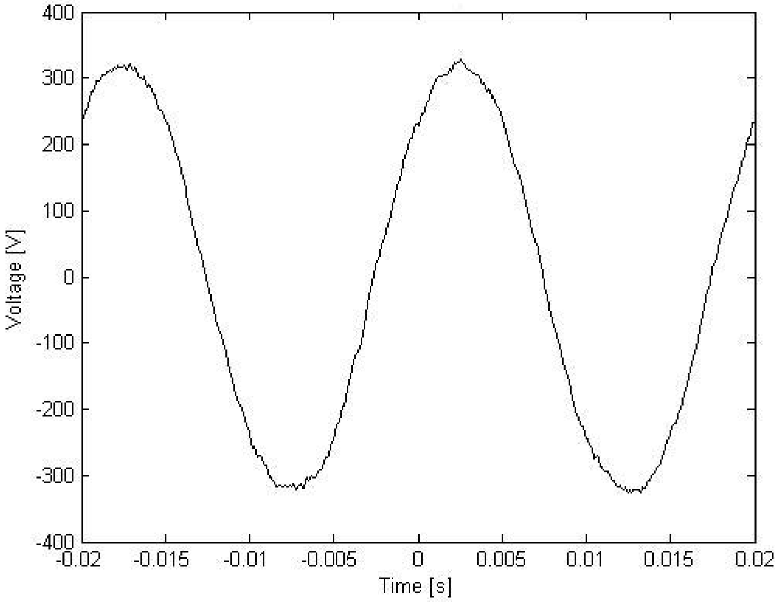


Figure 37. Load voltage

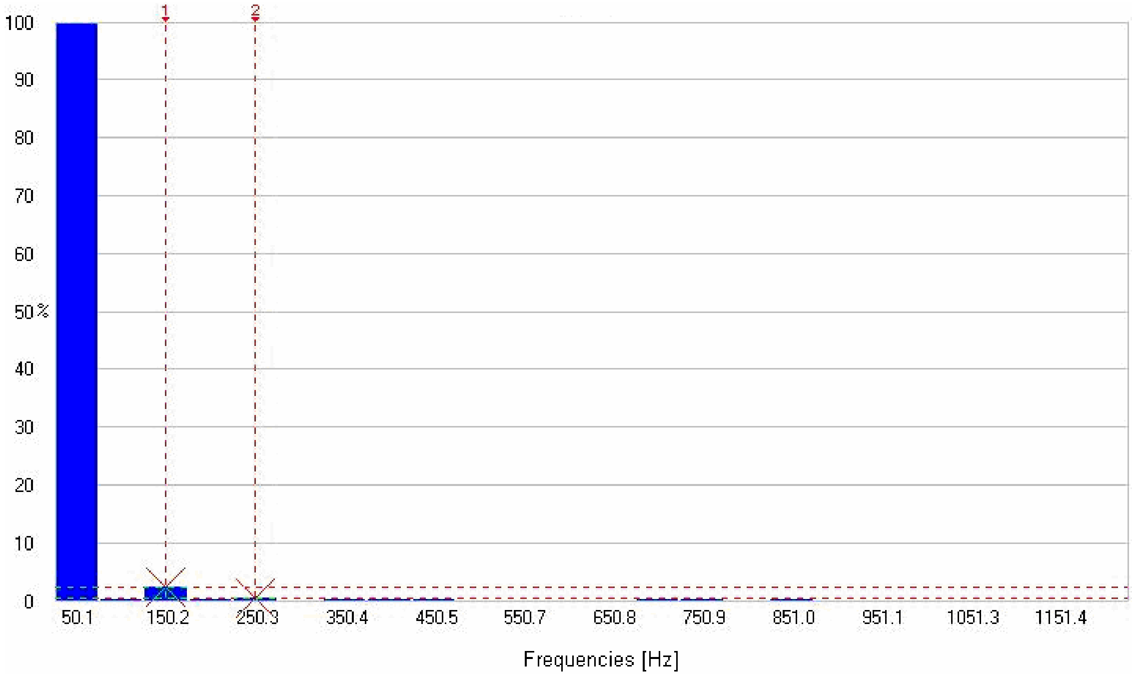


Figure 38. Load voltage spectrum. 3rd harmonic is 2.5%. 5th harmonic is 0.5%

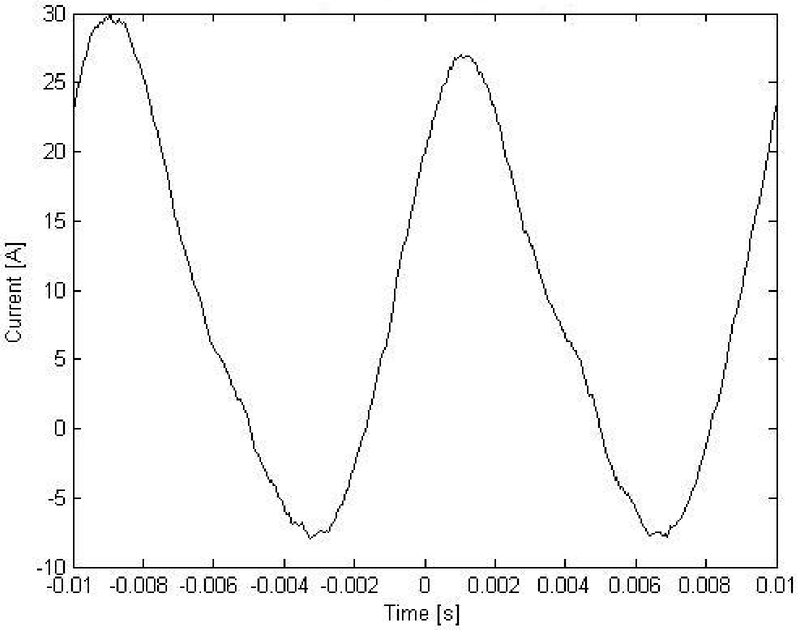


Figure 39. Sunny Island current (DC input)

### 5.1.4 Hybrid feeding

The last experiment in the first test assumes the case when the load power exceeds the DC generator generated power. It follows from this that some power is needed to be fed from the battery bank. In this case the power is supplied from both the Sunny Island and the Hydro Boy. The load is sill the same, see load parameters in table 3.

The Sunny Island AC output current and the Hydro Boy AC output current were measured in this test, see figures 44 and 46 correspondingly. Heavily distorted Hydro Boy output current is observed. The Sunny Island current curve is also really non-sinusoidal. But the load current and voltage diagrams are approximately the same with obtained current and voltage diagrams in the cases where the system regulated by the Sunny Island, see chapters 5.1.1 and 5.1.3. It means that the Sunny Island inverter is trying to compensate the disturbances of the system by supplying harmonics to the system in all operating modes.

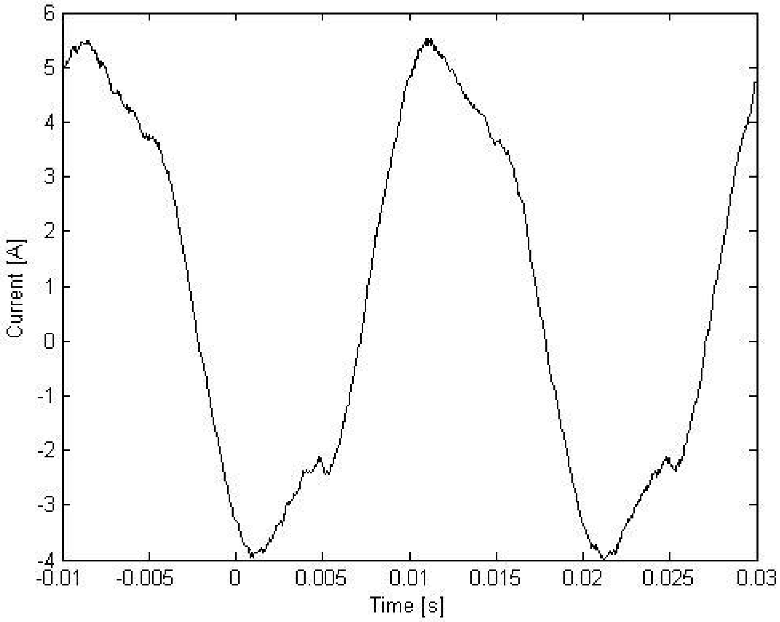


Figure 40. Load current

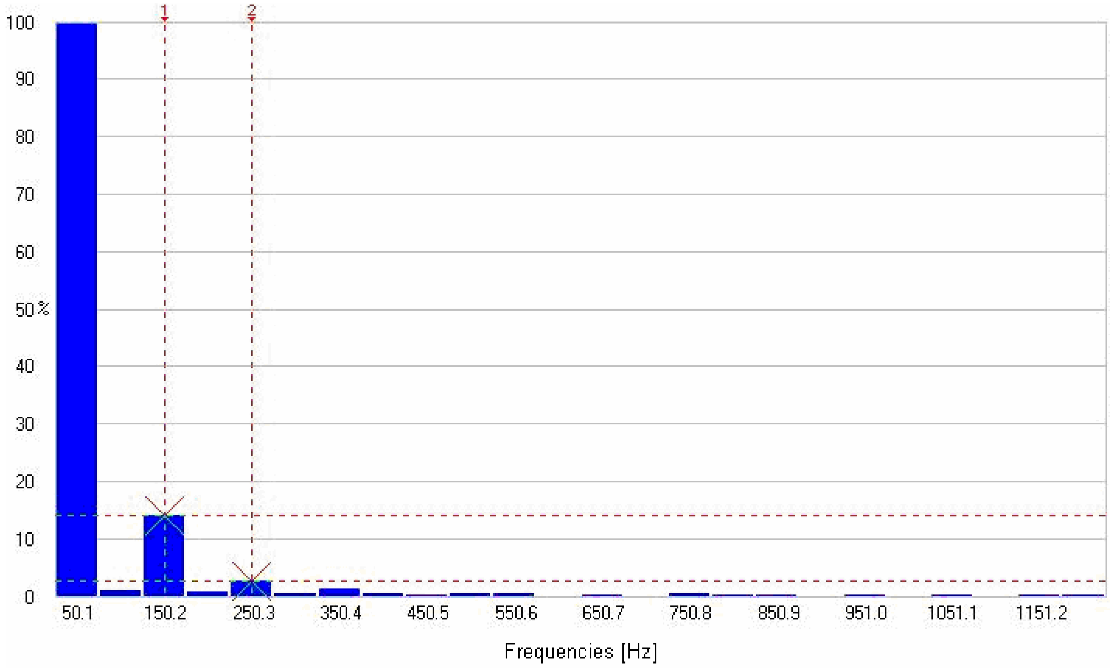


Figure 41. Load current spectrum. 3rd harmonic is 14.1%. 5th harmonic is 2.7%

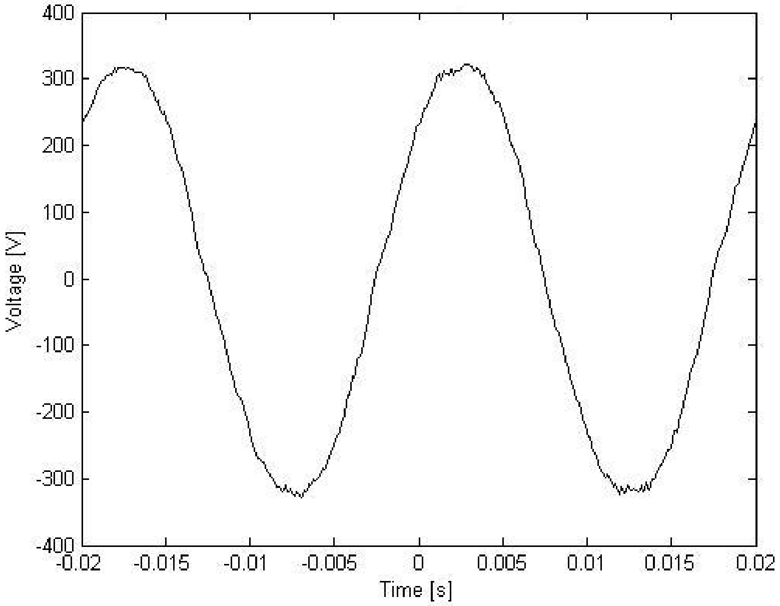


Figure 42. Load voltage

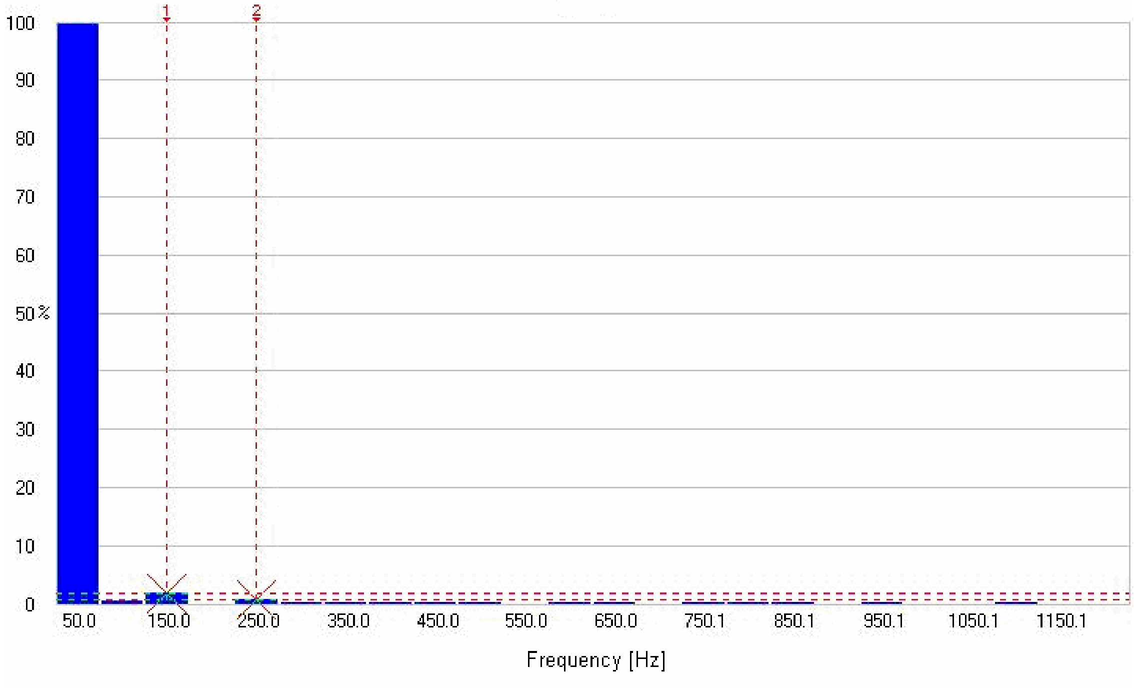


Figure 43. Load voltage spectrum. 3rd harmonic is 2%. 5th harmonic is 0.8%

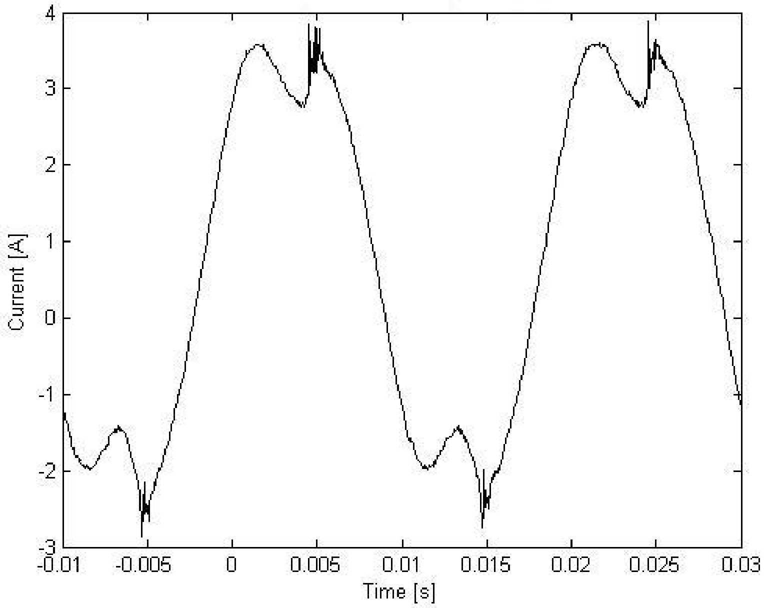


Figure 44. Sunny Island output current (AC output)

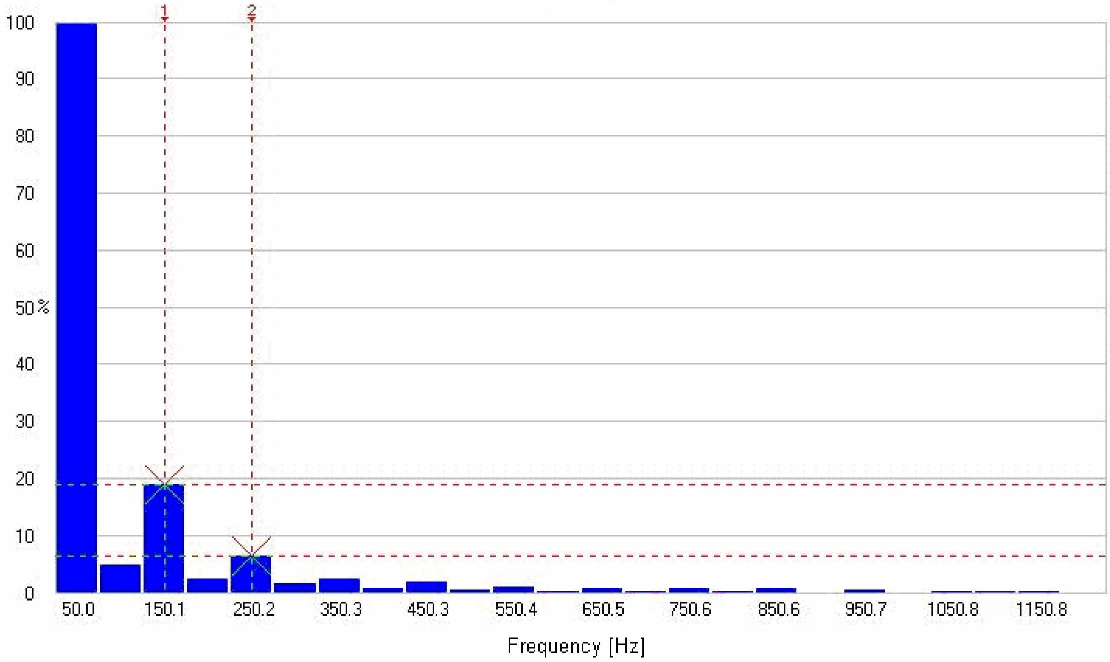


Figure 45. Sunny Island output current spectrum. 3rd harmonic is 18.9%. 5th harmonic is 6.4%

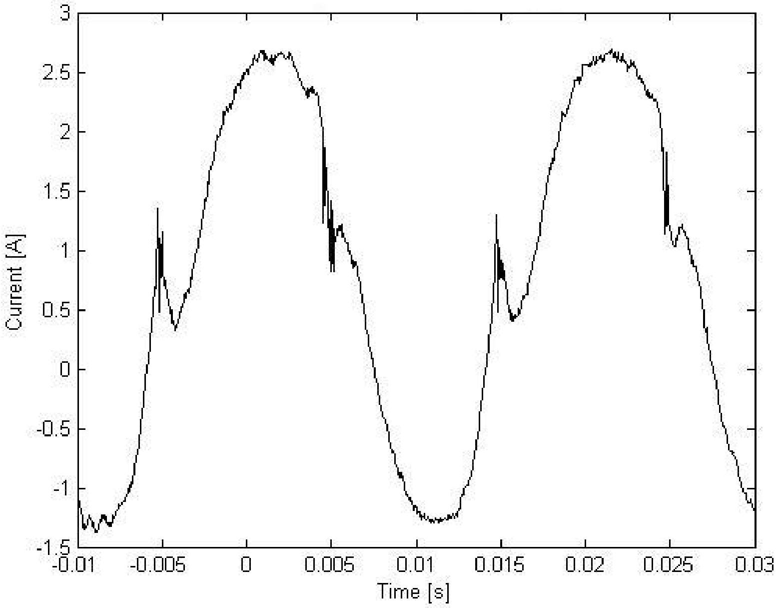


Figure 46. Hydro Boy output current

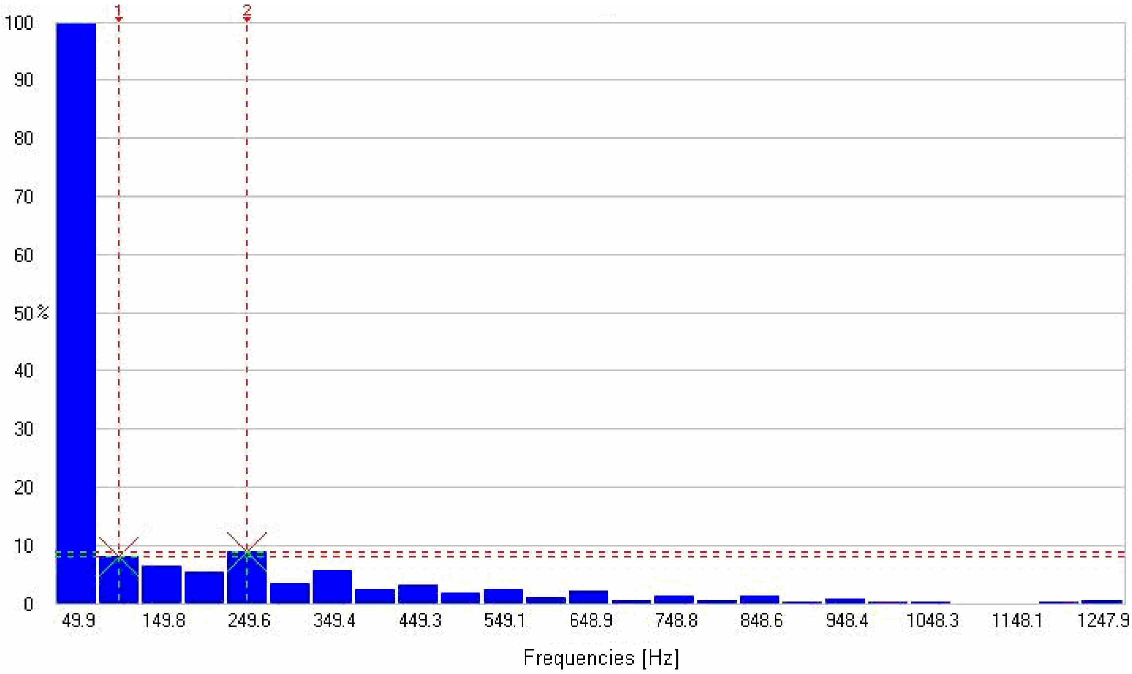


Figure 47. Hydro Boy output current spectrum. 2nd harmonic is 8.1%. 5th harmonic is 9%

### 5.1.5 Conclusion of test 1

In test 1 an important assertion was proved. The Sunny Island inverter which is the master inverter in the installed microgrid tries to maintain the sinusoidal voltage and to compensate the non-linear load by supplying harmonics to the system. The third harmonic of the load current in case when the load is fed from the system without the Sunny Island control, see chapter 5.1.2, was 20.1% of the RMS current value and the fifth harmonic was 5.3% of the RMS current value. At that time in the tests with the system under the Sunny Island control, see chapters 5.1.1, 5.1.3 and 5.1.4, the third harmonic of the load current did not exceed 14.7% and the fifth harmonic did not exceed 2.7%. The quality of the output power in the systems with the Sunny Island control is better than in the systems, controlled by the slave inverter Hydro Boy.

It explains the fact that the Sunny Island DC input current contains many ripples. A big amount of the reactive power is flowing throw the Sunny Island. The Sunny Island saves the excess energy in the battery and supplies the required energy to the system when it is needed. Evidently, the DC-link capacitors of the Sunny Island are too small, that's why such big ripples at the DC side of the Sunny Island are observed.

## 5.2 Test 2. Fourier analysis of the microgrid output current and voltage. Resistive load.

During the second test current and voltage waveforms and corresponding spectra were obtained when the load of the microgrid was fully resisted. Parameters of the load are shown in the table 4. The microgrid operated in islanded mode

Table 4. Load parameters

| | |
|---|---|
| Active power. $P$(W) | 700 |
| $\cos(\varphi)$ | 1 |

### 5.2.1 Hydro Boy feeding

The first case of test 2 concerned chapter 5.1.1. During the test all power comes from the Hydro Boy. Small excess of the generated by the DC source power flows to the battery. The battery DC current is equal to 0.7A DC. The following figures depict the current and voltage waveforms at different parts of the system during this test and the corresponding spectra.

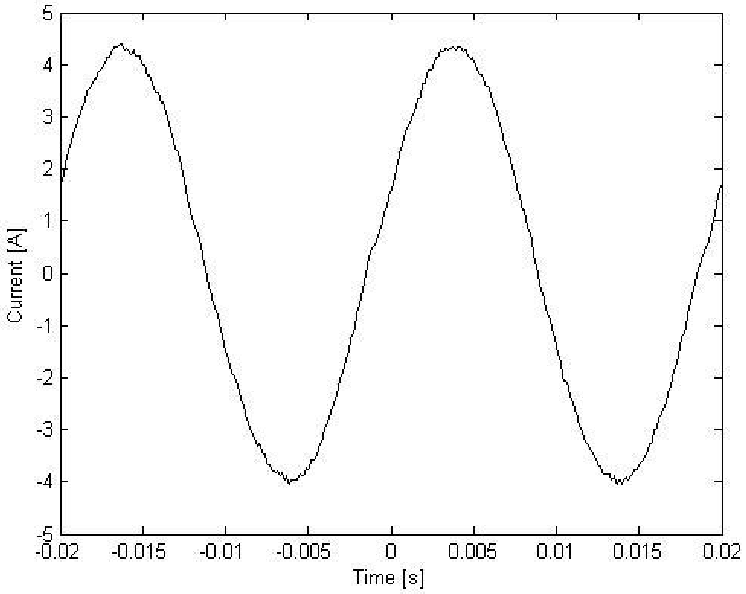


Figure 48. Load current.

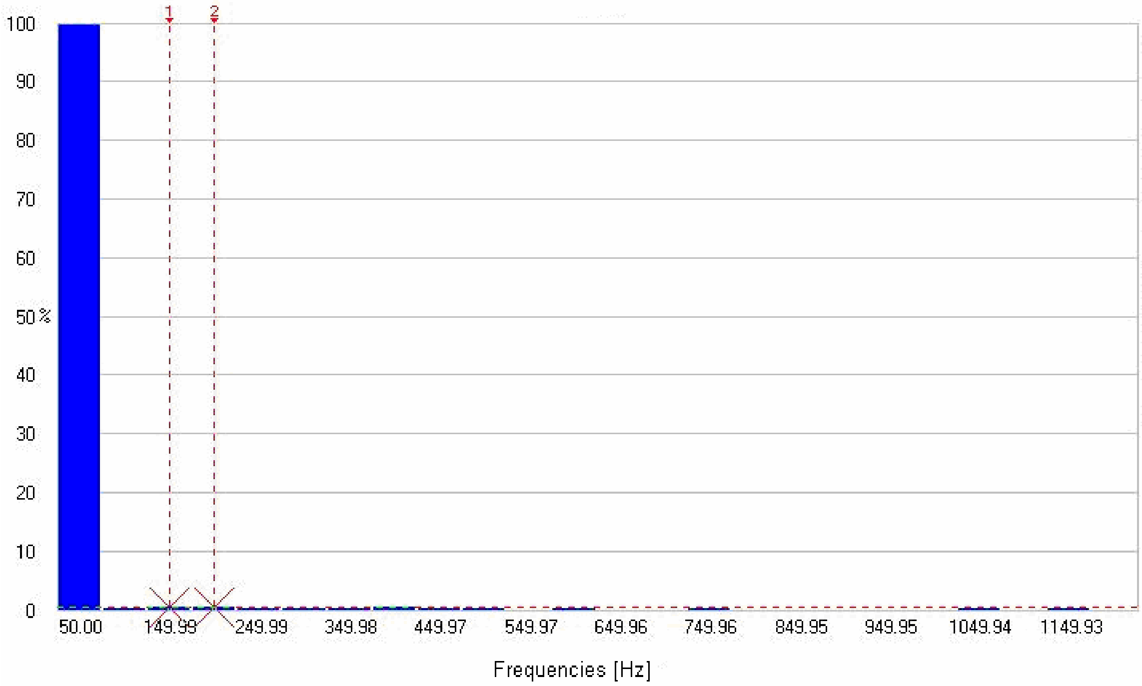


Figure 49. Load current spectrum. 3rd harmonic is 0.5%. 4th harmonic is 0.7%.

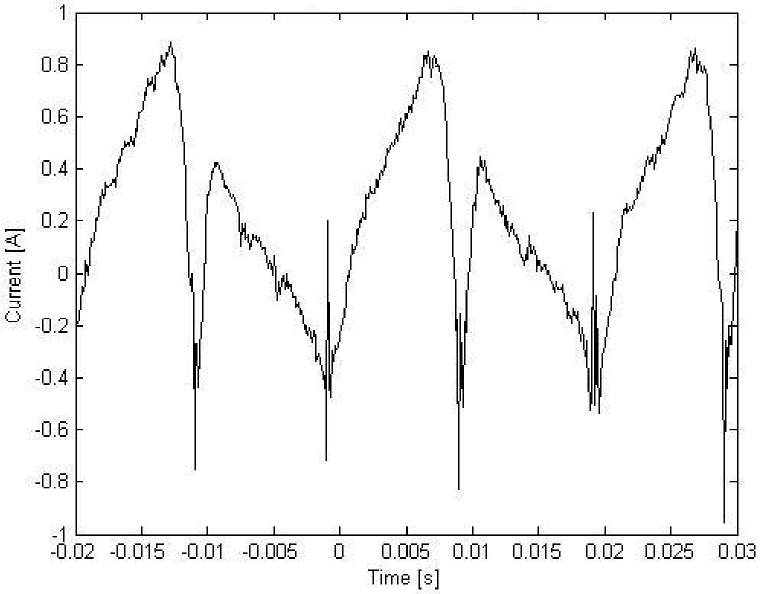


Figure 50. Sunny Island current (AC output).

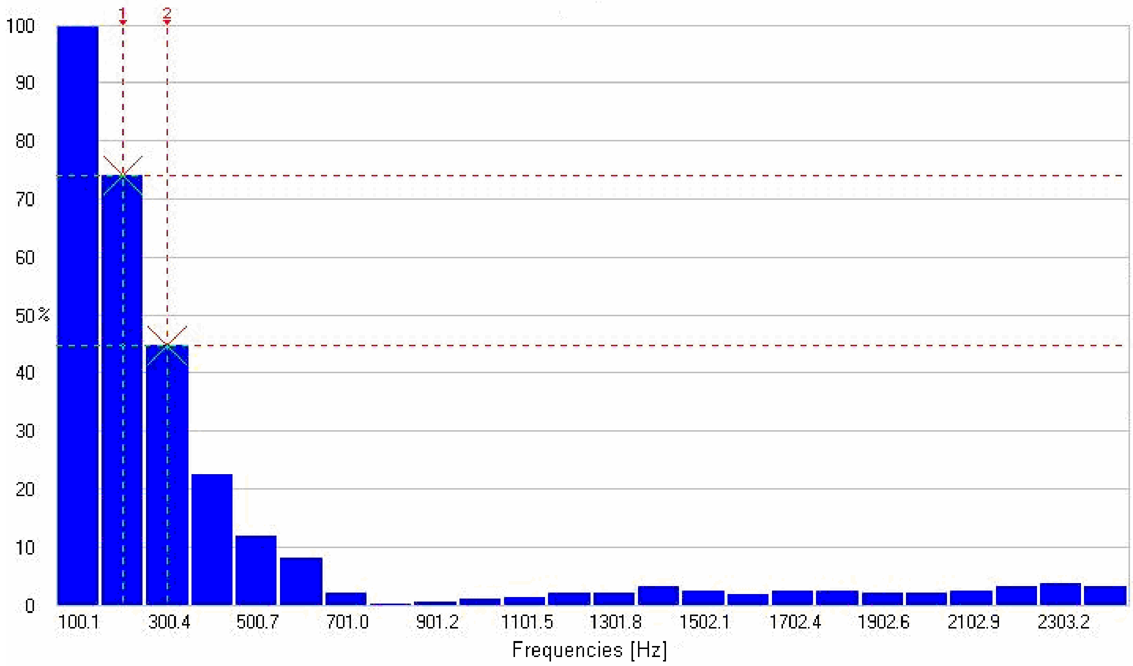


Figure 51. Sunny Island current (AC output).

In the cases of the hybrid and Sunny Island feeding current and voltage waveforms are greatly similar to the waveforms, which were obtained in this chapter. Resistive load current and voltage waveforms do not change with different sources.

### 5.2.2 Conclusion of test 2

When the power is fed from the Hydro Boy resistive load current waveform is nearly sinusoidal. The largest fifth harmonic is equal to 0.5%, see figure 49. We can observe a sinusoidal current waveform as it should be in the case of the resistive load. This test assumes the Hydro Boy feeding the resistive load. The power factor is equal to 1. We can see that the Sunny Island output power is really non-sinusoidal, see figure 50. But the amplitude of this current is really small compared to the case in the test from chapter 5.1.1, when were the same conditions with the inductive load. This means that the Sunny Island as a master inverter of the system also has a function of a power factor corrector. In this case, when the power factor is equal to 1 and the load is fed from the Hydro Boy, a little amplitude current signal is observed in the Sunny Island AC output.

## 5.3 Test 3. Fourier analysis of the microgrid output current and voltage. Domestic load.

### 5.3.1 Test description

In the third test a domestic load was connected. As a domestic load a laptop was chosen. The load current was 0.15A AC. The following load current waveform was obtained.

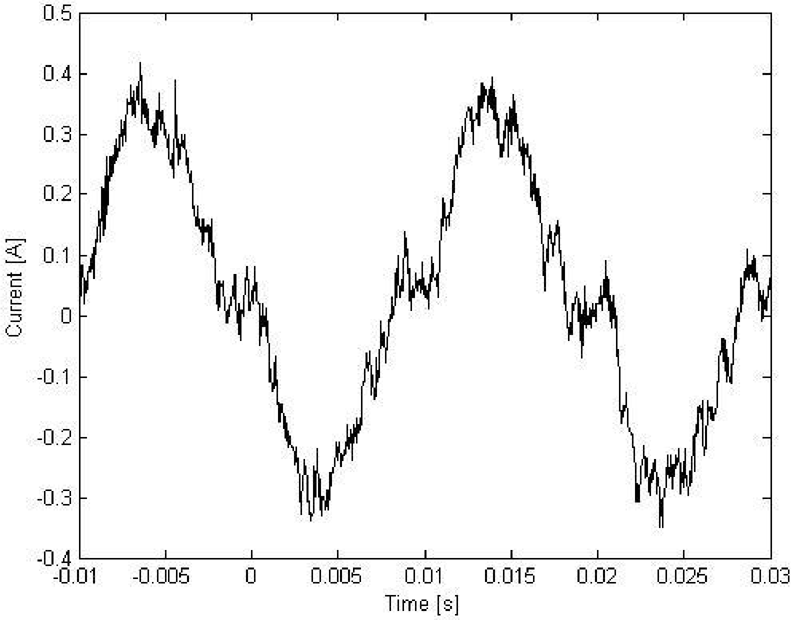


Figure 52. Load current .

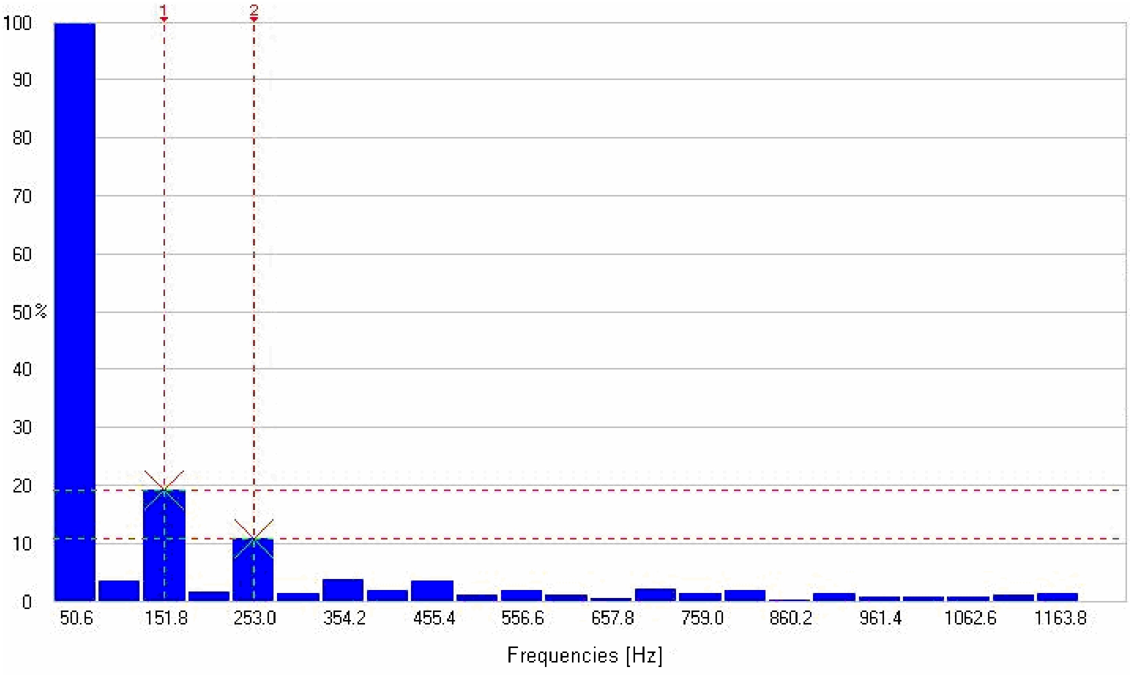


Figure 53. Load current spectrum. 3rd harmonic is 19.2%. 4th harmonic is 10.8%.

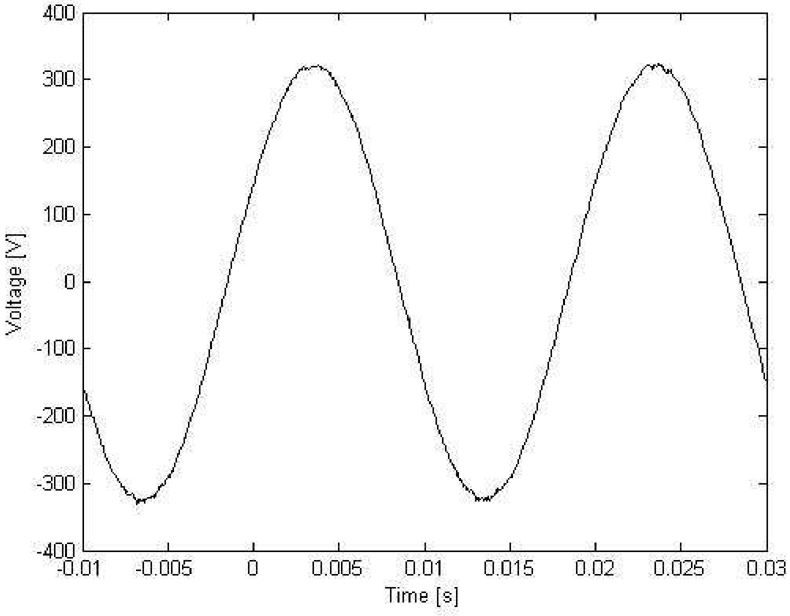


Figure 54. Load voltage.

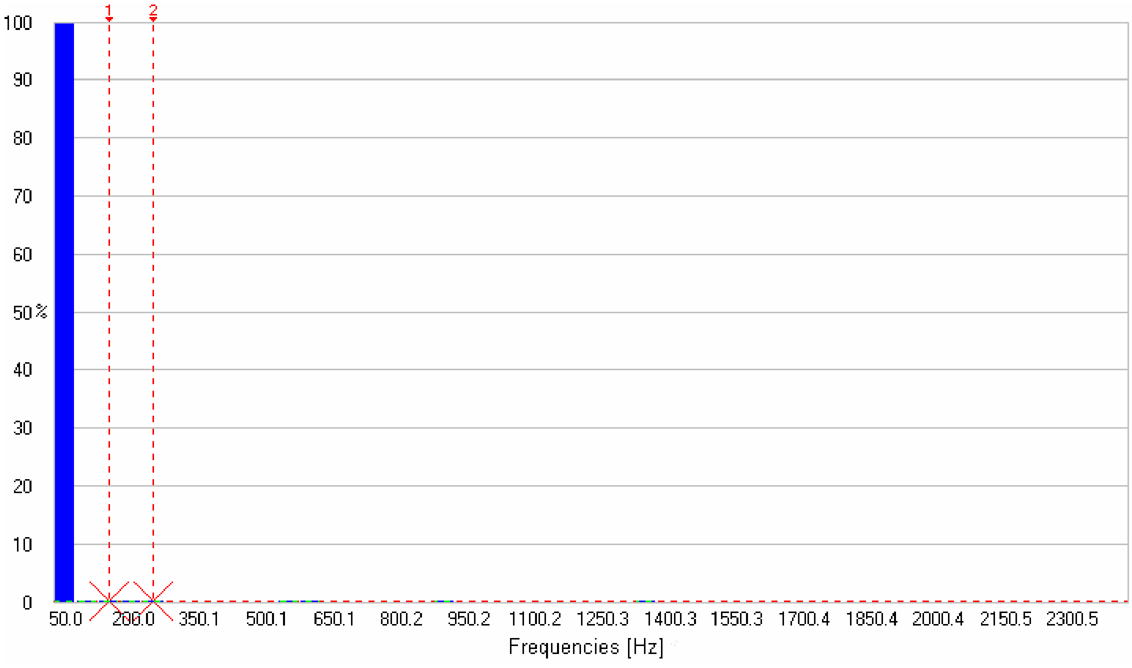


Figure 55. Load voltage spectrum. 3rd harmonic is 0.3%. 4th harmonic is 0.2%.

### 5.3.2 Conclusion of test 3.

In case of the domestic load, the current waveform at the load side is really different from the sinusoidal waveform. The PC seems to have a power factor corrected rectifier and the current waveform is acceptable. The largest third harmonic is equal to 19.2% of the RMS current value, see figure 53. Voltage in this case like in the previous cases remains sinusoidal without large disturbances, see figure 55.

## 5.4 Test 4. Droop control

### 5.4.1 Island mode

The test in this chapter verifies the frequency and voltage control strategies of the microgrid when the system operates in islanded mode. Figure 56 shows the active power of the Sunny Island inverter and how the control frequency changes during the test when the load grows. The following table shows the list of the loads which were used in this test.

Table 5. Load parameters

| Active power. *P*(W) | 168 | 304 | 600 | 693 | 750 | 960 | 1027 |
|---|---|---|---|---|---|---|---|
| $\cos(\varphi)$ | 0.98 | 0.98 | 0.98 | 1 | 1 | 0.79 | 0.81 |

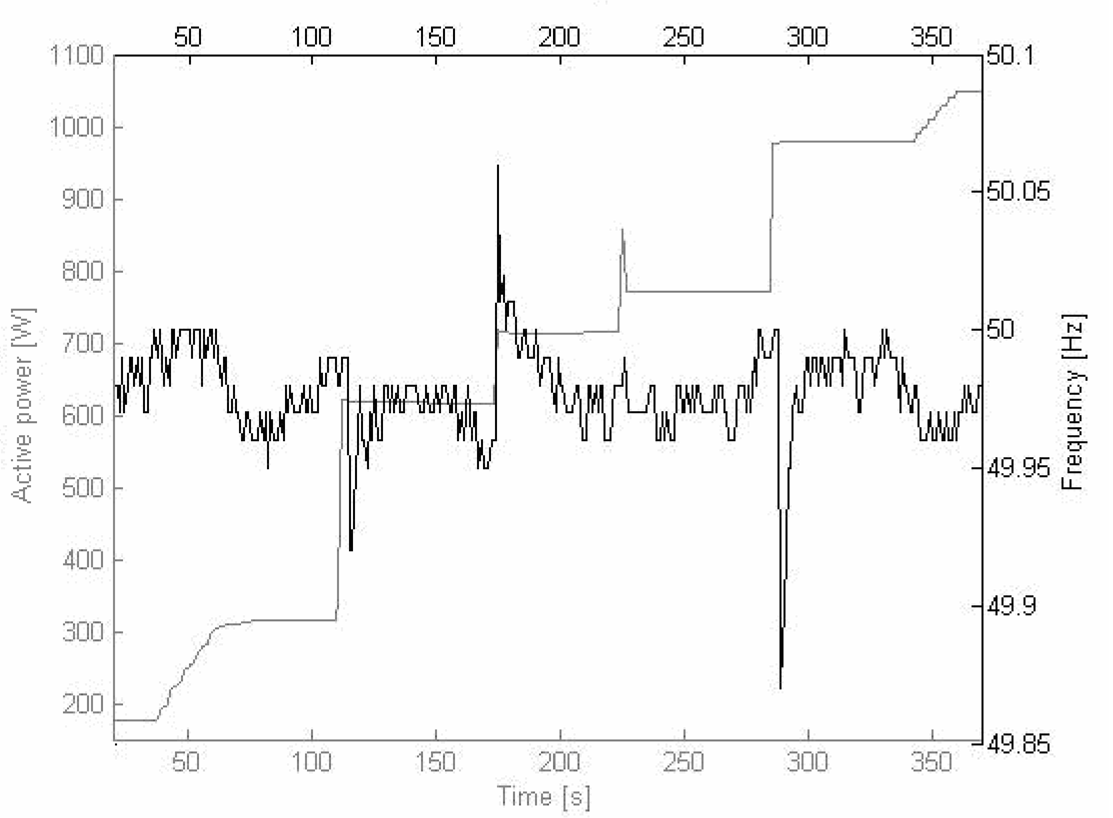


Figure 56. Active power/frequency control in an increasing-load-case.

It was explained in Chapter 2.3.4 that the local reactive power/voltage control required being in the systems with a large number of micro-sources, when the voltage and reactive power oscillations and circulating of large reactive currents in the system are observed. Figure 57 shows the reactive power/voltage control graph which was obtained during the tests. The system built comprises only one DC source, we can observe that the voltage remains constant. This test confirms the argumentations from chapter 2.3.4 about using of voltage control only in the case of a large number of the micro-sources in the system.

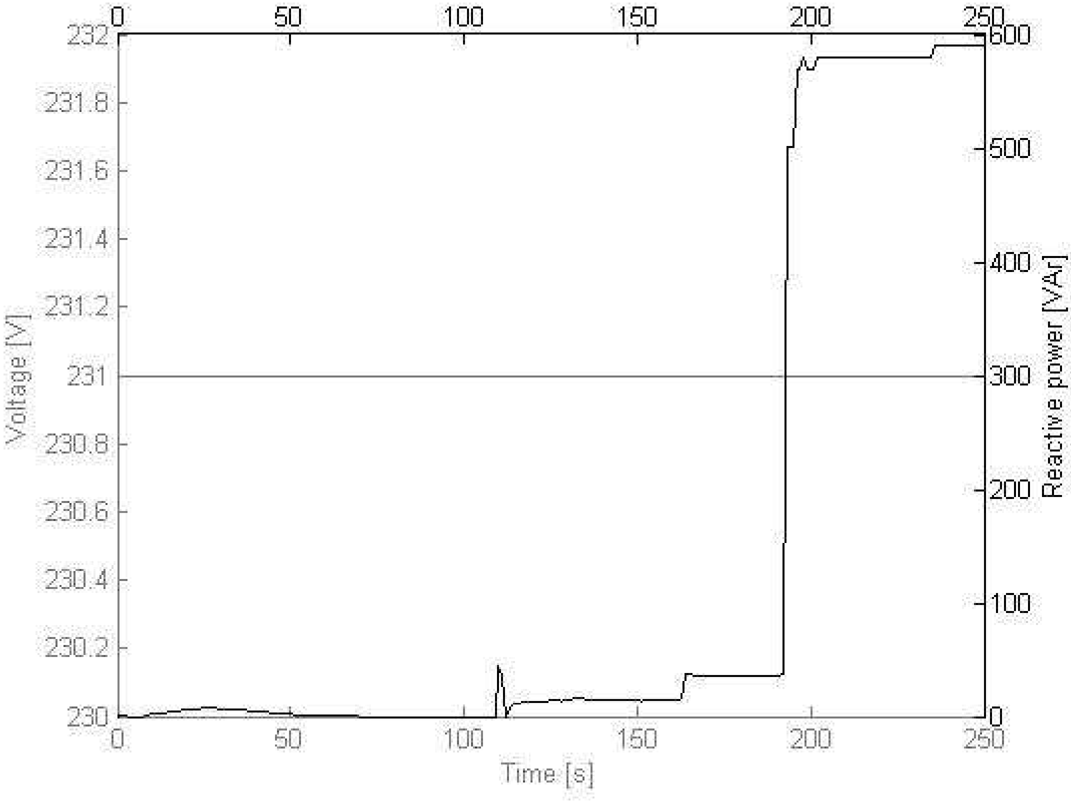


Figure 57. Reactive power/voltage control

### 5.4.2 Grid-connected mode

As it was mentioned in chapter 5.1.2, the microgrid built has one master inverter – Sunny Island. Hydro Boy is an on/off device which is a slave in the built system. I would like to notice that Hydro Boy operates really unstable when a large power or- and the utility grid are connected to the microgrid. The maximum power of the Hydro Boy is 1200W. The following test shows the active power/frequency control of the system and synchronization process of two inverters when the Hydro Boy transitioning from “off” state to “on”. Active power at the AC output of the Sunny Island and control frequency of the system were measured. Table 6 gives explanation of the carried test. -950W shows that the power flows inside the Sunny Island to charge the batteries.

Table 6. Test parameters

| Time period | I | II | III |
|---|---|---|---|
| Sunny Island active power (W) | -950 | 200 | 1150 |
| Hydro Boy active power (W) | 950 | 950 | off |
| Load active power (W) | off | 1150 | 1150 |
| Grid | on | on | off |

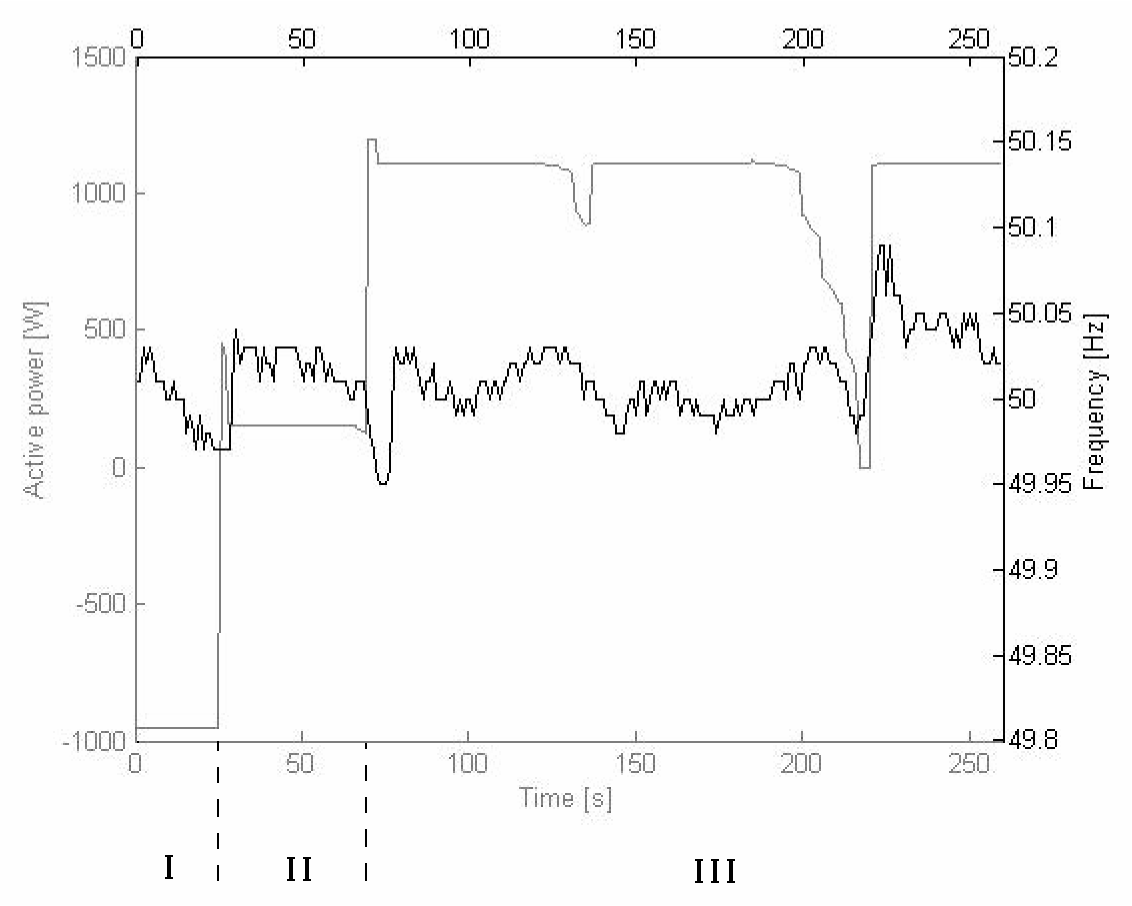


Figure 58. Active power at the Sunny Island AC output and control frequency

I – Hydro Boy is on and supplies 950W of power. Load is off, therefore the 950W of power charges the batteries. It is not needed to feed any power from the grid, therefore the grid current is approximately equal to zero

II – Connecting 1150W load. Hydro Boy gives only 950 watts of power, additional power from the batteries is needed. Load is supplied by both Sunny Island and Hydro Boy.

III – Grid connection turns off, Hydro Boy also simultaneously turns off. Power is fed by the Sunny Island. During this time period Hydro Boy tried to switch on two times. We can observe decreasing of supplied power from Sunny Island and again frequency regulation is presented.

The second part of the fourth test shows how the Sunny Island interfaces with the grid and the Hydro Boy. Table 7 gives an explanation of the carried test.

Table 7. Test parameters

| Time period | I | II | III |
|---|---|---|---|
| Sunny Island active power (W) | 725 | -100 | -90 |
| Hydro Boy active power (W) | Off | 815 | 815 |
| Load active power (W) | 725 | 725 | 725 |
| Grid | On | on | off |

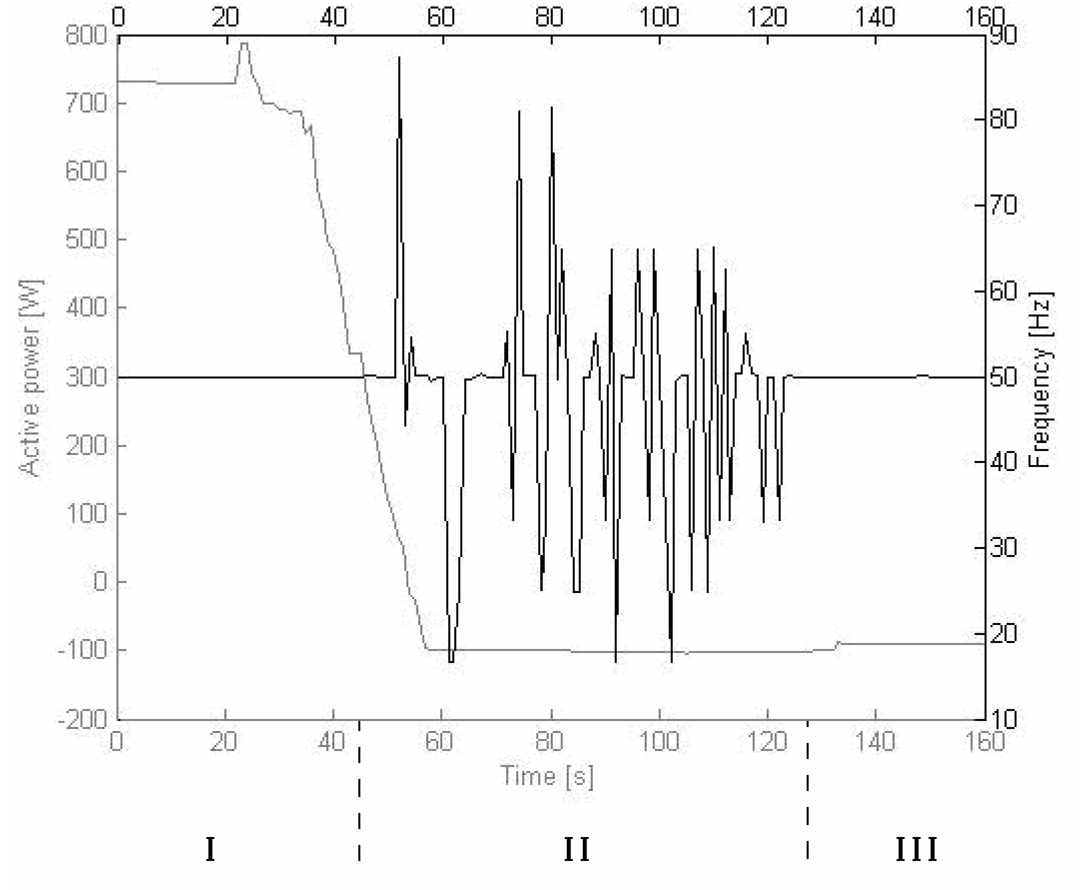


Figure 59. Frequency regulating

I – Hydro Boy is off. The load power is 725W. Regulation between the Sunny Island and the network occurs like in the first part of test 4.

II – Hydro Boy switches on. We can observe large frequency transients during the second time period. It is because the power flows to the Sunny Island from both the grid and the Hydro Boy.

III – Grid is switched off. Small amplitude frequency regulation is observed during this time period.

### 5.4.3 Conclusion of test 4

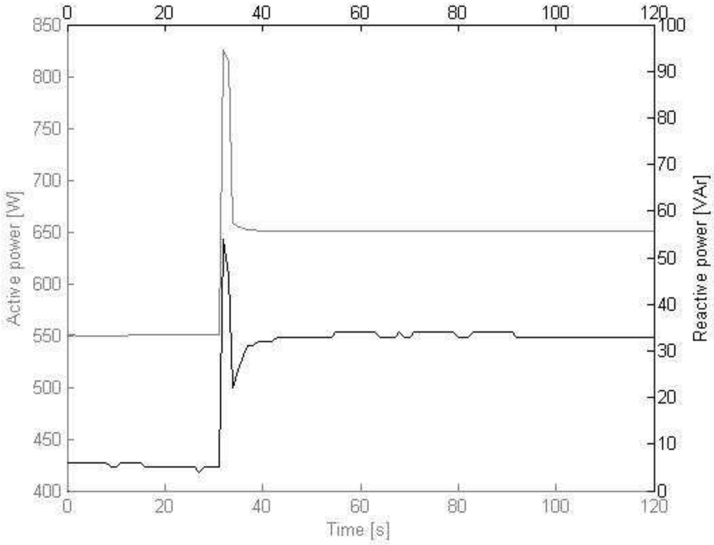
During test 4 droop control methods are verified. Argumentation in chapters 2.3.2 and 2.3.4 are proven in this chapter. In the built microgrid active power/frequency regulation is presented. Reactive power/voltage regulating is lacking in view of the fact that only one micro-source is used in the microgrid. According to figure 6, when the load power grows, the control frequency is required to be reduced in each mode of operating of the micro-grid. It can be observed in figures 56 and 58 for islanded and grid-connected operating modes correspondingly.

Tests in chapter 5.4.2 are slightly similar, but the second test is needed to verify the operating mode when both power from the utility grid and power from the Hydro Boy which is not supplied by the load flow to the battery bank through the Sunny Island. It occurs during the second time mode, we can observe high amplitude frequency regulating during this period of time, see figure 59.

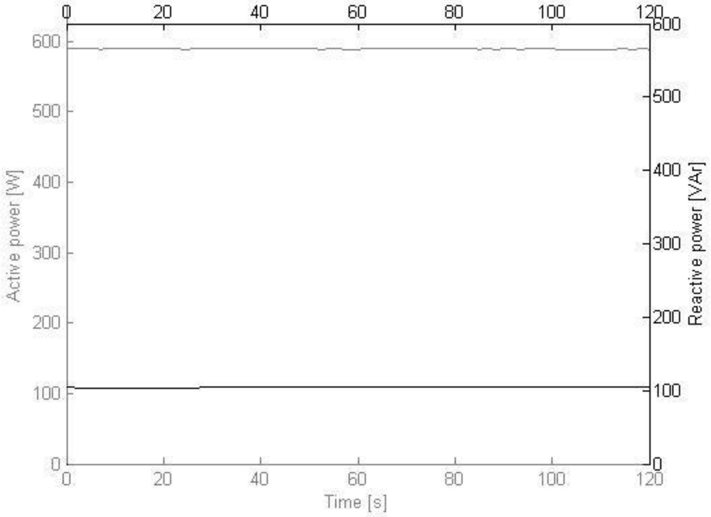
## 5.5 Test5. Regulations inside the system during the load power jump.

### 5.5.1 Test description

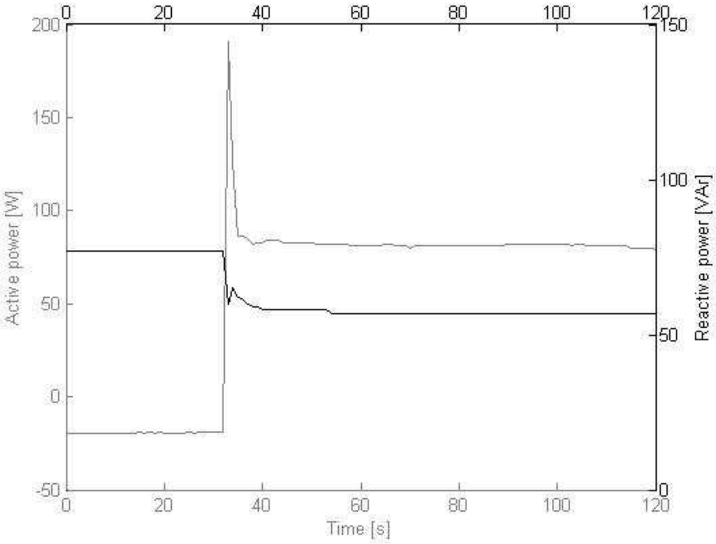
This test carried out to investigate the changes in the system when the load changes. Active load power changes during the test from 550 W to 650 W. Reactive load power changes from 8 VAr to 32 VAr. The following figure depicts the system alteration during the test.


0
20
40
60
80
100
120
850
800
750
700
650
600
550
500
450
400
Active power [W]
100
90
80
70
60
50
40
30
20
10
0
Reactive power [VAr]
Time [s]

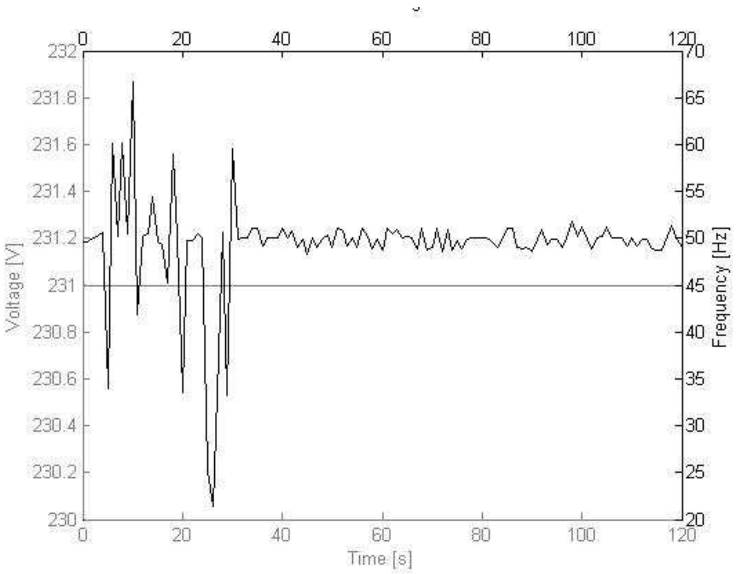
(a)


0
20
40
60
80
100
120
600
500
400
300
200
100
0
Active power [W]
600
500
400
300
200
100
0
Reactive power [VAr]
Time [s]

(b)


0
20
40
60
80
100
120
200
150
100
50
0
-50
Active power [W]
150
100
50
0
Reactive power [VAr]
Time [s]

(c)



(d)

Figure 60. Load changing test. Load active and reactive powers (a). Hydro Boy output active and reactive powers (b). Sunny Island output active and reactive powers (c). Microgrid control frequency and voltage (d).

### 5.5.2 Conclusion of test 5

During this test the power distribution inside the microgrid is observed. The load changes during the test. Figure 60 shows that Hydro Boy output power remains unchanged. Hydro Boy takes power from the reneweable energy source, according to the concept of the microgrids, chapter 1.4, maximum energy without drops and interruptions should be taken from the renewable source which is connected to the Hydro Boy and distributed to the microgrid. The Sunny Island, as it should be, distributes the energy inside the system. Before the 30th second of the test when the load power was less than the Hydro Boy output power, the Sunny Island sent the excess of the generated energy to the battery, negative active power is observed at the Sunny Island AC output during this time period, see figure 60 (c). When the load increased, the essential energy for the load’s supply was taken from the battery bank, see figure 60 (c). Herewith, in figure 60 (d) the control process is observed. The Sunny Island AC output voltage and frequency were measured during the test. Again, like in the test which is described in chapter 5.4.2 the frequency transients are observed during the time when the Sunny Island consumes the energy for the battery charging.

## 5.6 Test 6. Synchronization to the grid.

### 5.6.1 Test description

This test was held to investigate the synchronization processes between the grid and the microgrid. In the beginning of the test the microgrid was disconnected from the grid. The microgrid operated in the islanded mode. The load in this test was disconnected. The Sunny Island AC output current was equal to zero. After connecting the network to the microgrid, the synchronization process began. The following figure show the current transients during the synchronization, see figure 61. Measuring equipment was connected to the AC input and AC output sides of the Sunny Island which are connected to the utility grid and to the load correspondingly. At the end of the synchronization process the steady-state current from the main grid began feeding the system.

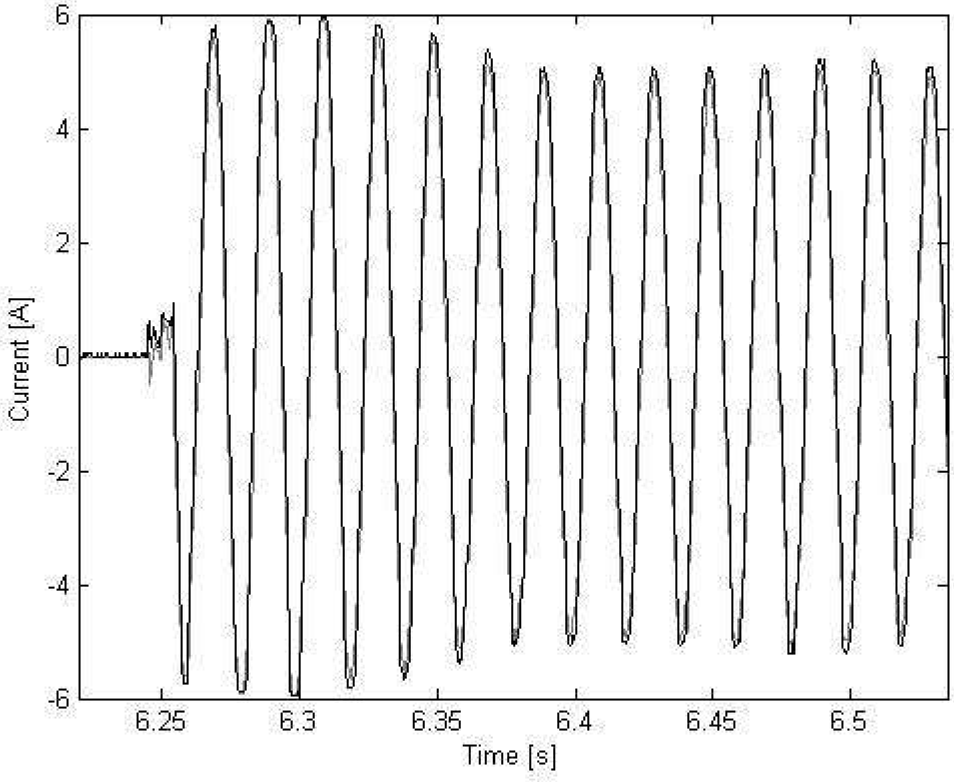


Figure 61. Current waveform during the synchronization process.

In the voltage synchronization test were the same conditions like in the previous current synchronization experiment. Measuring equipment for this case was directly connected to the grid contacts and to the Sunny Island AC output. In the beginning of the test the phase and peak values of the main grid and the microgrid's voltages were different, see figure 62. After turning on the key between the network and the microgrid, the synchronization process was beginning. As seen in figure 58 the phase shift and peak values of the grid voltage are coincide with the microgrid voltage in the end of the test.

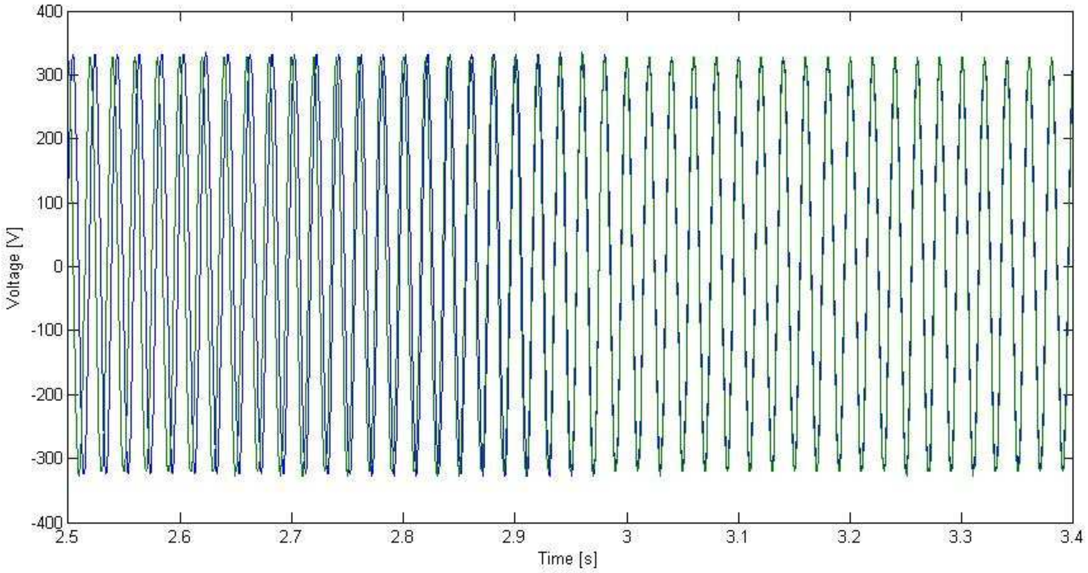


Figure 62. Voltage waveform during the synchronization process.

During test 6 the RMS values of the synchronized voltages were also measured. Figure 63 shows how the RMS values of the voltages are synchronized. In the beginning of the test the main grid and the microgrid are disconnected. Measuring equipment is connected to the main grid and to the microgrid. The microgrid operates in the island operating mode. The local load is fed from the batteries. The Sunny Island provides the power supply. The Sunny Island AC output voltage is equal to 231V, voltage 1 in figure 63. At the same time the main grid's voltage is equal to 228V, voltage 2 in figure 59. At the 30th second of the test the main grid is connected to the microgrid. We can observe the regulating process during which the microgrid's internal voltage is synchronized with the utility grid's voltage, see figure 63.

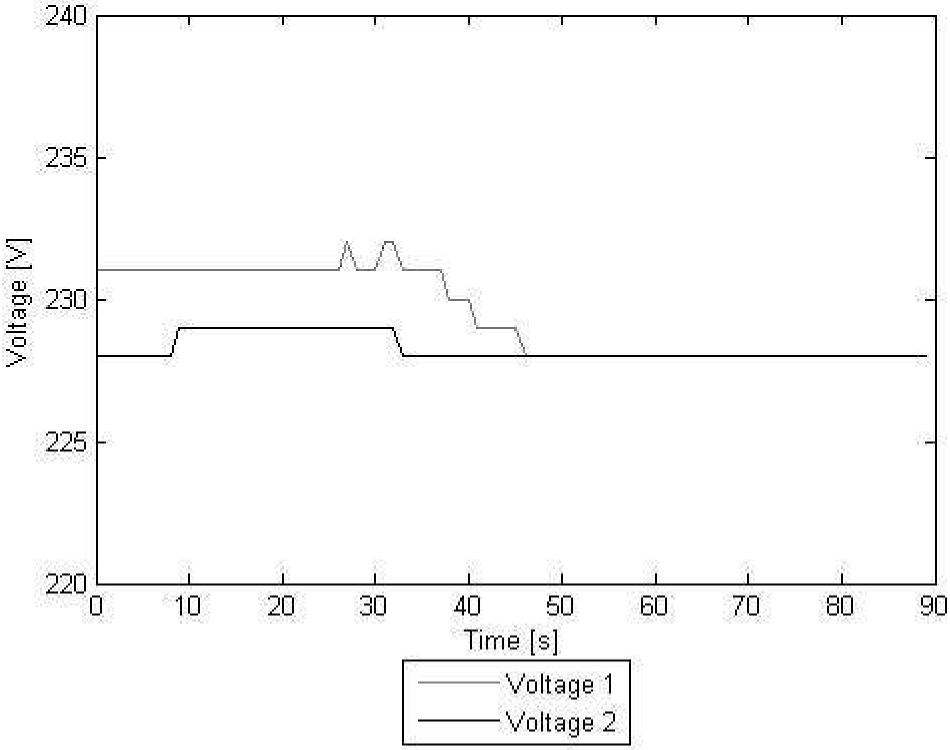


Figure 63. Synchronizing of the grid and the microgrid voltages

Figure 64 shows the frequency synchronization. The test was held at the same conditions like the test described earlier. Measuring equipment is connected directly to the grid and to the Sunny Island AC output. In the beginning of the test the grid and the microgrid are disconnected. Frequency 1 is a microgrid control frequency, frequency 2 is a grid frequency, see figure 64. Different frequencies are observed during the islanded mode. At the 60th second the network was connected to the microgrid. After the large transient in the microgrid the frequencies are synchronized. It can be seen in figure 64.

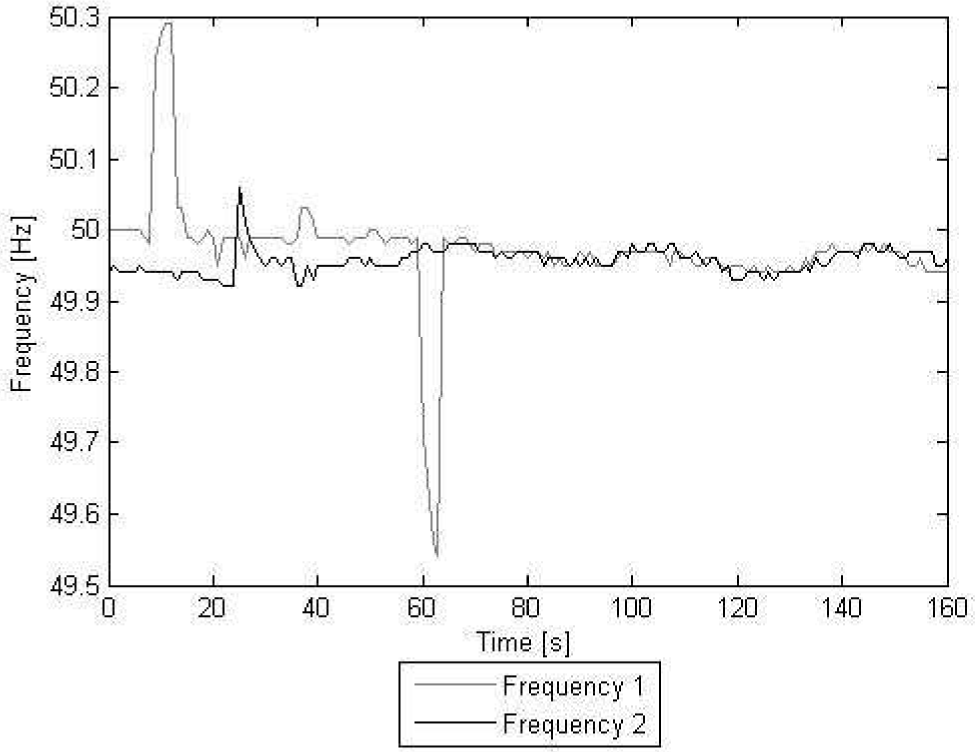


Figure 64. Synchronizing of grid and microgrid frequencies.

In the end of test 6, the power measuring test was held. The conditions of this test are the same as in the previous cases. In this experiment the main grid was connected to the microgrid approximately at the 50th second. Power distribution processes during the test can be observed in figure 61. During the tests and during this test in particular, not so good a feature of the Hydro Boy inverter was noticed. The Hydro Boy is an on/off device, it operates really unstable. The Hydro Boy turns off in the case of almost each operation with the microgrid. When the main grid connects or disconnects, when the large load connects or disconnects. In these cases the Hydro Boy is turning off and trying to synchronize with the system again. This can be seen in this test. In the beginning of the test the load is fed from the Hydro Boy, just 10W of the power is supplied from the battery, see figure 61. When the grid switches on, the Hydro Boy is immediately switching off, the Hydro boy output power drops while the Sunny Island output power grows, see figure 65. The protection device Ufe-ENS26, see chapter 4.4, does not allow for the power from the main grid feed the microgrid immediately after the connecting, there is approximately a 5 seconds delay between the switching time when the Hydro Boy power drops and the time when power from the grid is coming to the microgrid, see figure 65. The power from the grid exceeds the load power, because besides feeding the load the main grid charges the battery during the grid-connected operating mode. After approximately 40 seconds the network was disconnected from the grid. We can observe one microfrid’s feature concerned to the grid-connected operating mode: when the network is connected to the microgrid the load’s power decreases a little bit. After approximately 50 seconds the Hydro Boy automatically switched on. After that the microgrid transferred back to the island operating mode, see figure 65.

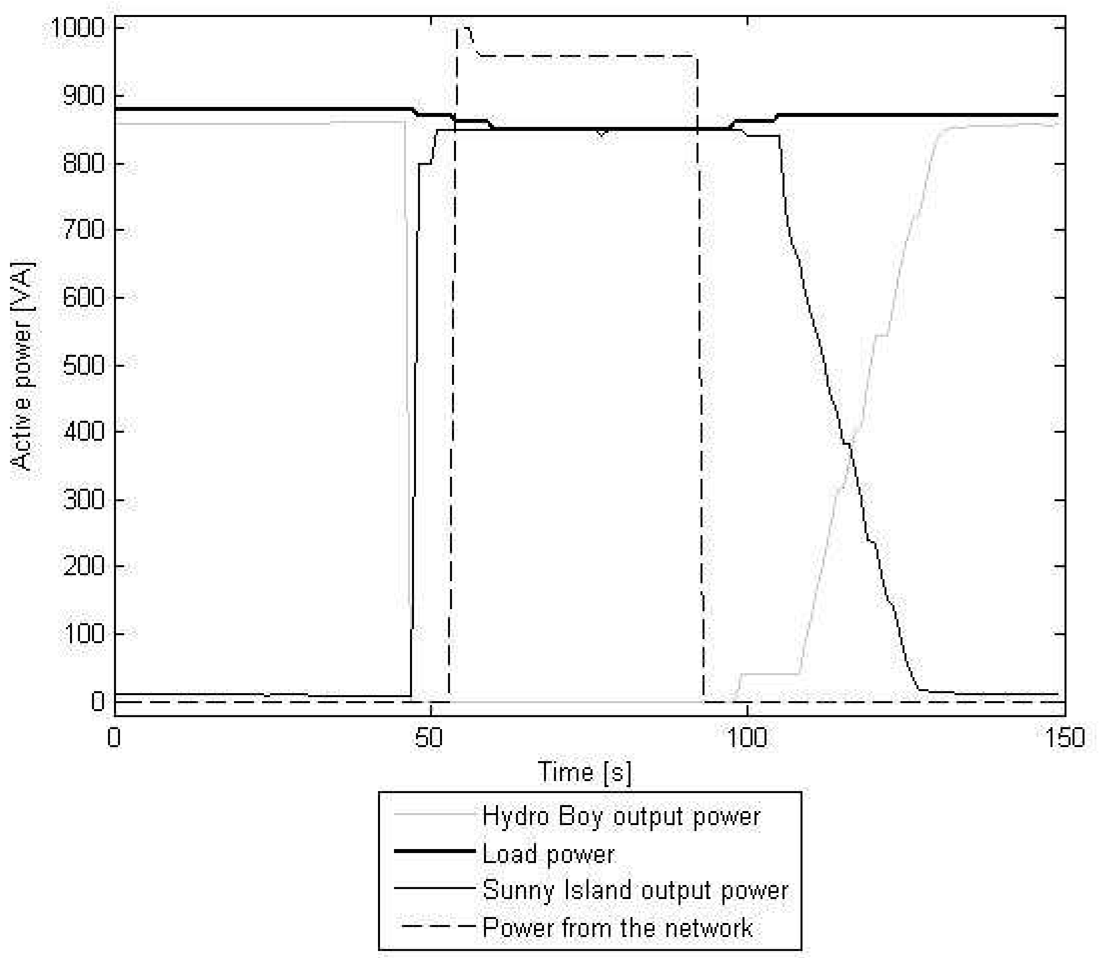


Figure 65. Power distribution.

### 5.6.2 Conclusion of test 6

This test shows how the AC voltages in the microgrids are synchronized. The voltage phase shift, voltage amplitude and frequency are synchronized rapidly after the grid's connecting. Also this test depicts the power distribution in the system, during different operating modes. The load power remains constant during the changing of the supply conditions inside the microgrid, but a small power drop is observed when the microgrid operates in the grid-connected mode.

## 6 Conclusions

Writing this thesis, much theoretical and practical work was done. Basic principles of microgrids' functioning, protection and control were explained. Besides, the thesis touches upon such important questions concerned to the microgrids as the advantages and difficulties of microgeneration, new generation technologies used in microgrids and market perspectives of the microgrids.

In the practical part of the thesis a small laboratory microgrid based on two inverters from SMA Technologie AG was constructed. The main operating modes of this microgrid were tested. The quality of the microgrid output power in each operating mode was evaluated. The experiments with built microgrid allowed proving the theoretical statements concerned to the microgrid's control and operating. After each experiment the conclusions and advices about this microgrid were done.

Based on the practical work done, it is possible to carry out the installed microgrid's investigations in the future. The thesis comprises the scheme and the main parameters of the built microgrid.

Possibility to use the renewable energy sources and such advantages of the microgrids as reliability, efficiency, quality of service, network support makes these systems a very competitive in the low- power markets. To my opinion the future of the microgeneration and electricity distribution depends on the microgrids' development.

But there are still many technical challenges and difficulties in this new power industry area. Nowadays the microgrids are not in advanced stage of development. I’m really interested in this area, and I would like to continue my investigations about the microgrids in the future.

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# Appendix A

## MATLAB code for tests 1, 2 and 3:

```
data1 = dlmread('file_name');
time1 = data1(:,1);
current1 = data1(:,2);
Fs = 1/abs(time1(1)-time1(2));
figure(1)
plot(time1, current1)
xlabel('Time [s]')
ylabel('Current [A]')
```

**MATLAB code for tests 4, 5 and 6:**

```
data1 = dlmread('file_name');
data2 = dlmread('file_name');
time1 = data1(:,1);
current1 = data1(:,2);
time2 = data2(:,1);
current2 = data2(:,4);
Fs = 1/abs(time1(1)-time1(2));
figure(1)
hl1 = line(time1,current1,'Color','r');
ax1 = gca;
set(ax1,'XColor','g','YColor','r')
ax2 = axes('Position',get(ax1,'Position'),...
        'XAxisLocation','top',...
        'YAxisLocation','right',...
        'Color','none',...
        'XColor','k','YColor','k');
 hl2 = line(time2,current2,'Color','k','Parent',ax2);
xlabel('Time [s]')
ylabel('y_label')
```

**MATLAB code for the last experiment in tests 6:**

```
data1 = dlmread('file_name');
data2 = dlmread('file_name');
data3 = dlmread('file_name');
data4 = dlmread('file_name');
data5 = dlmread('file_name');
time1 = data1(:,1);
time2 = data2(:,1);
time3 = data3(:,1);
time4 = data4(:,1);
time5 = data5(:,1);
power1 = data1(:,2);
power 2 = data2(:,3);
power 3 = data3(:,4);
power 4 = data4(:,5);
power 5 = data5(:,6);
Fs = 1/abs(time1(1)-time1(2));
figure(1)
plot(time1, power 1, time2, power 2, power 4, power 4, time5, power5)
xlabel('Time [s]')
ylabel('Active power [VA]')
```