SELINUS UNIVERSITY

Analyse, optimization and modelization prototype of measurement and control cabinet for protection (ICCP) system

A DISSERTATION

Presented to the Faculty of Engineering and Technology

in fulfilment of the requirements

for the degree of

Doctor of Philosophy

in Electronics and communication Engineering

BY:

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Declaration

" I hereby declare that this PhD dissertation was written by myself. I have quoted all the results of the established readings and the carried-out research "

Haydar Darwish

Acknowledgement

First of all, I would like to express my great gratitude to **Professor Salvatore Fava** for executing the review, support and encouragement.

I sincerely thank my company for introducing my PhD and for the assistance to submit me the essential equipment and devices that I needed to finish my program.

Finally, I show my deep appreciation to my family for their continued support and encouragement during my research.

Abstract

One of my essential duties as developer and designer project engineer is to analyse and modelize a new prototype of an Impressed Current Cathodic Protection (ICCP) system. An ICCP system is used in order to prevent corrosion, in this case the protection is obtained by the ICCP system. The measurement and control unit are part of the ICCP system, which consist of different parts. The most important part of this unit is the AC / DC converter.

On the basis of studying, analysing and accumulated experience, a prototype of ICCP has been identified. The components of the measurement and control box had been selected just as the model that was built for ICCP. The scheme for that box has been drawn and the main converter had inclusively been chosen as well for TDK-HWS controller. Thereafter, followed by the risk analysis and the lifetime evaluation.

An important requirement of the final product is that the system satisfies the CE / IEC standards concerning immunity, emissions and harmony. The Immunity and emission test results obtained from the AC / DC transformation data sheets of the manufacturer (TDK-Lambda). After literature review, it was found that all results were within limits. The test results on the harmonic were not available, therefore the harmonic tests were performed during this project. The harmonic meets the CE / IEC standards. The class of the unit was determined. It is determined that it fulfilled to class A, the highest class.

A test set-up is created, in order to obtain the carried-out results. The test consists of measuring using variable load. The devices (PLC, FieldLogger and Data Taker DT80) have been programmed, beside the variable load resistor was built up. The harmonic, power factor and efficiency were the main measurements. A data logger is used to measure all parameters at the same time.

A measurement at 1 load lasted 55 seconds. 27 different values of resistance are used by 40 voltage steps (0.5 V from 24V to 5V), that means 1 test takes 16.5 hours. The variable resistor is made by the use of the lamps that was controlled by a PLC. By determining the resistance per lamp, the power used was predicted. The different values of the variable load have been optimized by the use of several parallel resistor circuits. The test should be executed in six steps, which gave no accurate result, then through a procedure in six steps with breaks, which gave satisfactory results. The test through an automatic procedure of 27 steps which is carried out in order to achieve higher resolution. The automatic measurement is done by making use of a Mitsubishi PLC (hardware) and the Alpha 2 program (software), in order to save time. The measurement on the harmonic current of the prototype is performed using the test set-up. The harmonic measurement results are within the CE / IEC standards.

The results were obtained for a prototype of ICCP through three tests, after that the results were analysed and optimized. The test of the harmonic current was conducted to determine whether the harmonic current HWS fell within the standard. Through a formula and tests were THD-I and THD-U determined and compared. The primary current limiting principle had to be worked out and the relationships defined in formulas/graphs in such a way that it could be implemented in software.

Furthermore, the input current was limited to a maximum phase current of 16A at 400VAC. The input current is a function of the output power. This relationship was derived between the output power and the input current.

A prototype was built to simulate a test. A simulation model of the harmonic currents was made which is based on the measurement results. This model is used to simulate the effectiveness of the filter in MATLAB. This is to determine whether there are more active or passive filters could be used.

The prototype of the measurement and control unit has been designed and tested. It fills the immunity and harmonic emission standards up. It has been found that the input current is not larger than 16 A. The use of a filter is not needed in this case, because the results of the harmonic without the indicated filter which meets the CE / IEC standards.

Finally, a conclusion had been reached with the results and recommendations. It is recommended to determine the imbalance of phases current. It is also recommended to adjust the created test set-up so that it can be used for other ICCP systems. It is also important to recommend that the assessment graphs will be standardized. Yet, it is recommended to study and investigate whether a lightning protection is required.

Version control

Version	Date	State	Remarks
1.0	06-06-3031	Concept 1.0	First draft CH.1 by Haydar Darwish
2.0	22-07-2021	Concept 2.0	Final dissertation

List of Abbreviations and Symbols

- *Abbreviations*

Abbreviations	Meaning
AC	Alternate Current
CE	Conformity European
CIS PR	Comate International Special des Perturbations Radioélectroniques
DC	Direct Current
DCM	Direct Current Models
DUT	Device Under Test
EFT	Electrical Fast Transient
EMC	Electromagnetics Compatibilities
FAT	Factory Acceptance Test
FO	Functional Ontwerp
ICAF	Impressed Current Anti Fouling
ICCP	Impressed Current Cathodic Protection
ICE	International Electrical Commission
IEC	International Electrotechnical Commission
MATLAB	MATrix LABoratory
MGPS	Marine Growth Preventive System
NEN	Nederlandse Norm (Dutch Standard)
PF	Power Factor
PLC	Programmable Logic Controller
RF AMP	Radio Frequency Amplifier
RTU	Remoted Terminal Unit
SCADA	Supervisory Control and Data Acquisition
THD	Total Harmonic Distortion
TO	Technical design

- *Symbols*

Symbol	Define
Cos phi	Cosinus Φ
d	Differential
f	Function
Pin	Power input
Pout	Power output
Rb	Resistance
Rn	New resistance
η	Efficiency

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Contents

1. Introduction

In the first section of this chapter, the types of corrosion and their protection are studied and analysed. In addition to the protection from corrosion is precisely presented the basic details of ICCP.

The paragraph 1.2 is intended for the studies of a general review of the most important research related to the topics of the dissertation. Results and conclusions reached presented and compared to what has been discussed in this dissertation. In Paragraph 1.3, the problem of definition and description are formulated, along with the objectives and the method of process.

1.1: The basics of corrosion and ICCP

1.1.1: Definition and types of Corrosion

Corrosion is the attack of materials by the action of their environment, and in particular the attack of metals by means of electrochemical reactions. Damage due to purely mechanical influences, such as erosion and breakage lead to a collision or collapse, but they are not counted as corrosion. The best-known types of corrosion are the attack of metal surfaces by oxygen and water in the air, such as the rusting of iron and the green changed colour of copper. However, corrosion can also occur in a watery environment and with high temperatures and it can also include ceramic materials and plastics. Corrosion requires safety risks and high costs for instance the failure of load-bearing structures, leaks and blockages in sprinkler systems. Every second steel loses around five tons of its worldwide value and this brings about corrosion. The costs are estimated at 3% of the Gross National Product. Different types of corrosion can be classified as: [1]

- Atmospheric corrosion
- Galvanic corrosion
- General biological corrosion
- Liquid salt corrosion
- Corrosion in liquid metals
- High temperature corrosion
- High temperature oxidation

See the following Corrosion schedule:

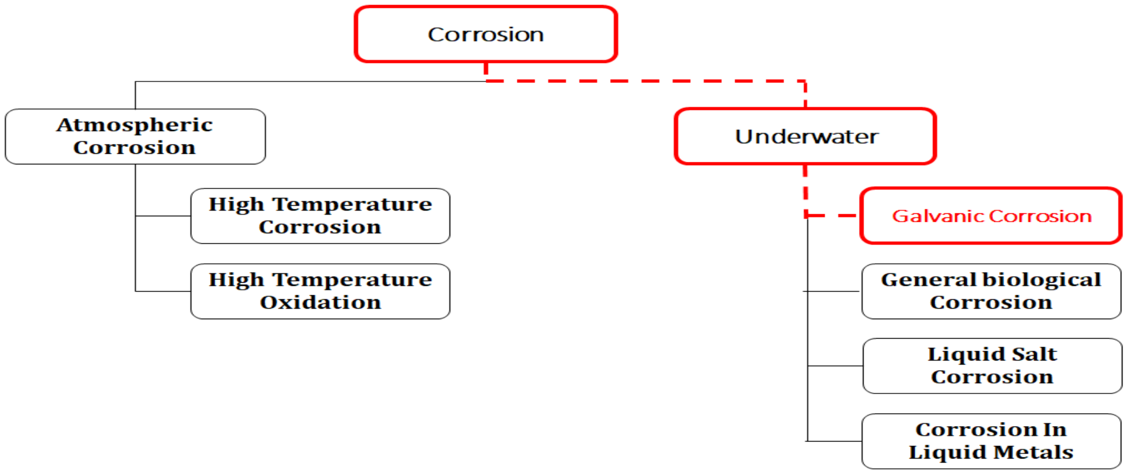

Fig. 1.1: Corrosion diagram

Galvanic corrosion

Galvanic corrosion (The path is marked in red in Fig. 1.1) is a form of electrochemical corrosion that occurs when an electrolyte with water is interacted and that leads to an electrical circuit and so called the galvanic cell. And what happens in a galvanic cell is an exchange of electrons and one of the two metals will corrode. The active, corroding metal is the anode, which transfers electrons to the less active metal, which is so-called the cathode. After the anode has completely disappeared which gives rise to corrosion. Furthermore, the cathode will start a corrosion process again, depending on the galvanic position. In galvanic corrosion, a metal corrodes more quickly if it comes into contact with a good quality metal provided that both are in contact with an electrolyte.

[1] Manual ICCP - AKBv3 Impressed Current Cathodic Protection System

A metal can corrode Conversely less quickly if it comes into touch with a less grade metal as long as both are in contact with an electrolyte. Therefore, an Impressed Current Cathodic Protection (ICCP) can be used to reduce the galvanic corrosion.
In order to make the anodic position more cathodic artificially with the supplement of electrons, then the entire surface becomes cathodic and thus there is no solution for the metal can come by. This process is called cathodic protection. The only condition to achieve it, is to supply sufficient electrons. This can be achieved by introducing negative charge into the structure, i.e., by making the potential more negative. Corrosion is a major threat and ICCP protection is one of the important systems that offers a solution against corrosion and this concept will be covered through this project.

1.1.2: Protection of corrosion

The ICCP protection is used to stop corrosion in underwater steel structures. Experience has shown that ICCP is a cost-effective system and impressive way to extend the age assumption.
The production of dissolved metal ions and free electrons which causes material loss. With an overage of electrons in the anodic region, the electrons are not taken out from the iron-containing molecules, but they react with the hydroxide ions. This process leaves the iron molecules sound and prevents corrosion and material damage. The addition of anodes or impressed current completes the cathodic protection system. This project contributes to the corrosion protection process by means of the measurement and control cabinet (cathodic protection system). The excess of electrons is provided by an external power source. See the following figure:

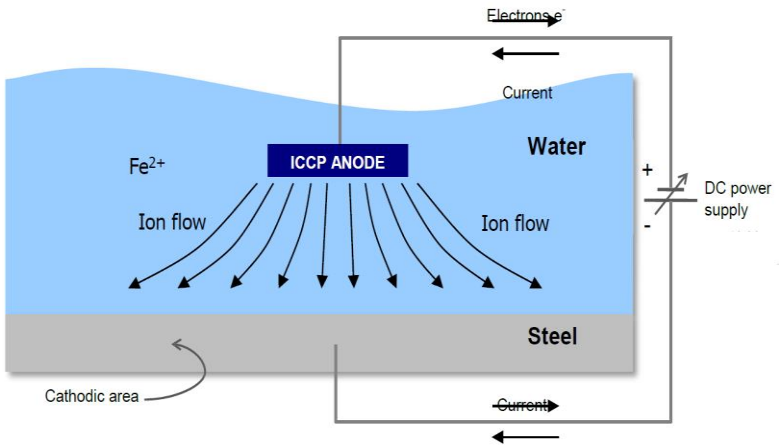

Fig. 1.2: Cathodic protection by impressed current

Without ICCP protection, metal looks like the following figure:

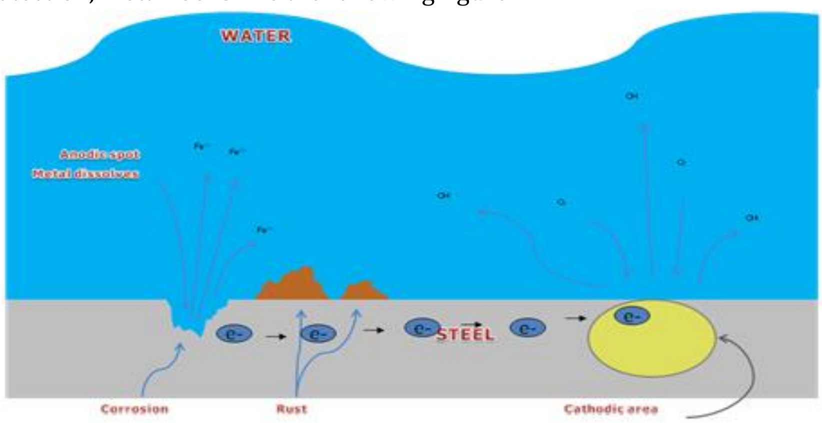

Fig. 1.3: Metal without ICCP protection

The ICCP system only protects the external parts under water, not tanks, intake and exhaust pipes, bow thrusters, parts above water. Separate cathodic protection must be used for these parts. If necessary, the automatic control requires more current for protection. See the following figure:

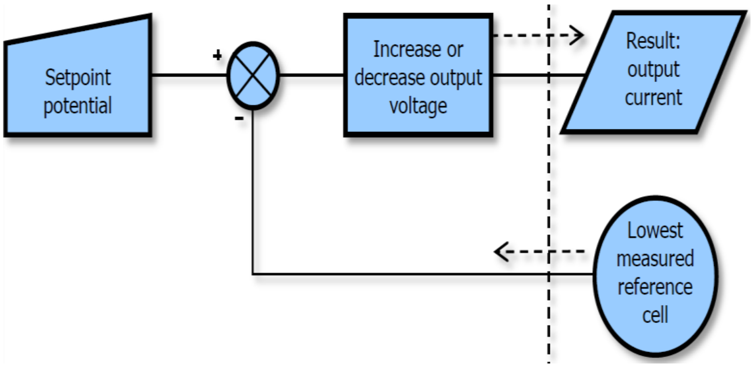

Fig. 1.4: General ICCP algorithm

The system takes only into account the reference cell that has the lowest protection. The output current increases as the voltage rises. There are two limits:

- maximum current
- maximum voltage

These limits together with the physical layout of the active components which determine whether the set potential is reached.

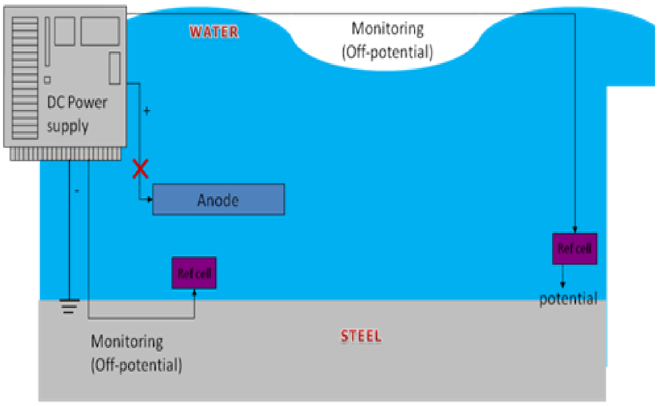

Fig. 1.5: Cathodic protection by impressed current

The ICCP consists of several parts: See the following ICCP- diagram:

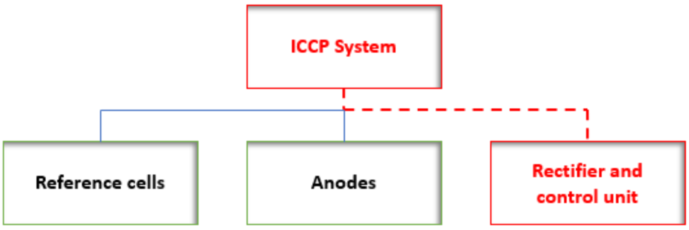

Fig. 1.6: ICCP-diagram

The system is supplied with current anodes that provides the necessary current to protect against harmful effects such as corrosion. The current anodes are made of a mixed metal oxide, a coated titanium support plate encapsulated in a strong plastic container. The anode can be placed in the body of a ship and then welded into the tank.

Reference cells

The protection level is measured through the reference cells. The measured value is passed on to the power supply unit which in turn increases or decreases the current sent by the anodes. The reference cell is made from high purity zinc.

Rectifier and control unit

Current is sent to the anodes. The incoming values from the reference cells ensure the optimal protection which increases or decreases the current. The power supply is connected to the main network by means of a rectifier unit. This rectifier produces the required voltage. The AC-DC rectifier can consist of several components.

The AC-DC rectifier is controlled by a microprocessor printed circuit board, which calculates the required current. Power is sent through the positive terminal to the anodes and returned to the body via a return connection through the earth. This project includes study of the rectifier and the control unit as well focuses on creating a model of prototype of ICCP. Project application concerns the off-shore wind turbines such as the following figure:

Fig. 1.7: Off-shore windmill protection

1.2: Literature review

In the last decade a lot of researches have been done regarding the Impressed Current Cathodic Protection (ICCP) system. There are different researches related to the content of this dissertation, it will be discussed as follows:

The first research is the implementation of Cathodic Protection (CP) station. Also, a self-adjusted DC-DC converter is designed and implemented for this purpose, and Aluminium anodes designed and manufactured for the sake of approving the proposed CP station operation. An edit has been made on the main empirical formula that is previously intended for the design of the same CP system. The first conclusion of this study gives the flexibility in order to choose the anode position which is giving the best coverage of protection. The second one shows the designed converter that performs a continuous change of the applied anode to cathode voltage. [2]

In second research paper focuses on the corrosion prevention of buried metal structures in general and gas pipelines in particular, by the novel method of Impressed Current Cathodic Protection (ICCP) which uses electrical current from an external DC power source for its operation just as the current dissertation. The efficiencies of the power sources are then analysed and compared according to the climate effects, the versatility effects, the intensity of power output, their operational limitations and their initial, running and maintenance costs. ICCP system is used for protecting larger metallic structures where the current requirement is high and external DC source is required. The efficiency of each DC source has been thoroughly analysed after comparing their technical and cost efficiencies. Based on measured results, the technical efficiencies of the Solar system were found a promising solution in the rate of corrosion, since it has tendency to deliver more constant DC power to an ICCP system both with hot and cold temperatures as well as in high and low resistivity environments. This research will aid companies and industries to select the right type of external DC source while designing the ICCP system depends on climate, output power intensity and cost efficiency for corrosion protection of underground pipelines. [3]

As for the other paper the identification model of ICCP using an Adaptive Neuro-Fuzzy Inference Systems ANFIS (Adaptive Network based on Fuzzy Interference System) was implemented.

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[2] **International Journal of Power Electronics and Drive System (IJPEDS), Vol. 11, No. 1, March 3030**

[3] **IOP Conf. Series: Materials Science and Engineering 414 - 013034, ICAET, 3018**

The identification model consists of four inputs which are the aeration flow rates, the temperature, conductivity, and protection current, and one output that represented by the structure-to-electrolyte potential. The used data taken from an experimental CP system model; type impressed current submerged sample pipe carbon steel. Secondly, two control techniques are used. The first control technique uses a conventional PID (Proportional-Integral-Derivative) controller, while the second is the fuzzy controller. The PID controller can be applied to control ICCP system and quite easy to implement. But it required very fine tuning of its parameters based on the desired value. Furthermore, it needed time response more than fuzzy controller to track reference voltage. So, the fuzzy controller has a faster and better response. In this paper, the parameters of an impressed current cathodic protection system have been identified using ANFIS technique and controlled by using a PID and fuzzy logic controller. From this research, it can be concluded that the cathodic protection current raise for increasing the parameters such as temperature, conductivity and the aeration flow rate of the saltwater solution. And the cathodic protection current required for the old pipe greater than the new pipe segment for protection. An ANFIS has been proven to be efficient in identification model of ICCP system. The PID (Proportional Integral Derivative) controller can be applied to control ICCP system and it is quite easy to implement. But it required very fine tuning of its parameters based on the desired value. [4]

According to the project included in this dissertation, the prototype of ICCP has been modelized by analysing all the chosen components. An important requirement of the final product is that the system fulfils the CE / IEC regulations immunity, emissions and harmony.

The setup test should be created, in order to obtain the required results. The measuring test includes using variable load. The harmonic factor, power factor and efficiency have to be tested through using the data logger, besides the use of PLC. A simulation model of the harmonic currents has to be made, according to the measurement required results. The MATLAB (MATrix LABoratory) simulation will be used to design the filter of prototype cabinet. For more details, see the following paragraph:

1.3: Problem definition

1.3.1: Main problem:

The major problem which is submitted through the project, how to should be a model of the measurement and control cabinet (ICCP) confirmed with immunity, emission and harmonic standards. As well, how are the measurement results and the graphs analysed and optimized

1.3.2: Sub problems

• How to derive the mathematical formula of the output power for ICCP?

• How simulation program and model of ICCP should be used for verification and which filter should be designed and simulated?

1.3.3: Objectives

• The main objective is to analyse, optimize and modelize of ICCP with the help of the measuring instrument (PLC, FieldLogger, oscilloscope, mustimeters, function generator, etc.). As well as to model a prototype of the (ICCP).

• Deriving a new mathematical formula for the output power of ICCP. In addition, the model includes the limit value of the input current.

• Minimize harmonic currents of the input filter of ICCP by using simulation program such as MATLAB.

• Validate the model of ICCP by comparing with other standards.

1.3.4: Research scope

Research is focused on the field of electrical and electronics technology to achieve the required model. In order to derive the output power formula, by employing advanced mathematics and control systems. While testing the proposed model, needed to program the PLC. Moreover, taking into the account of the selection of MATLAB as one of the engineering applications for the Simulation procedure.

1.3.5: Research requirements

The purpose of the mission is to design and test the measurement and control cabinet for the ICCP and a prototype will be installed. The prototype has to comply with the CE / IEC regulations.

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[4] "Identification and Control of Impressed Current Cathodic Protection System", Vol.13 No.3, 3016

The assignment also includes the input current limit to a maximum of 16 A per phase at 400VAC and an input filter to minimize harmonic currents.

Modelling a prototype ICCP

• How are the measurement and control cabinet designed?
• How are the connections of the measuring and control cabinet located?
• How is a risk analysis with regard to the age assumption made?

Immunity, emission and harmonic standards

Regarding the immunity, emission and harmonic standards, the following requirements have to be considered:

• How is a test setup made for the measuring equipment (the FieldLogger, the Data Taker) and the variable load by programming the PLC?
• How is the current harmonic testing performed?
• How to analyse and optimize measurement results and graphs?

Controller limitation

• How the maximum values of the current, voltage and power are set?
• How is current limit testing performed?
• How is the input power formula derived?

Filter modelled

• Which simulation program and model are used for verification?

1.3.6: Procedure

The most important components of the measuring and control cabinet that are required for this are already known and selected. They are all almost identical. This has to be worked out in details, tested, optimized and realized. The electrical diagram should be fulfilled.

The requirements of the cabinet are:

• The prototype should limit the primary current drawn to a maximum phase current of 16A at 400VAC.
• The prototype has to give the total output current of 360 A, produced by 6 AC / DC converters, i.e., three parallel converters of 180 A together and three separate converters of 60 A each.
• The prototype complies with the CE / IEC regulations.
• Perform the test for the maximum current harmonic with no more than 3.30A.
• Additional parts are also needed, to be specified an input power supply filter to be simulated to minimize the current harmonic (<3.30 A).

The overall methodological diagram of project is shown: (For more details, see Appendix A- Expected Plan of the project)

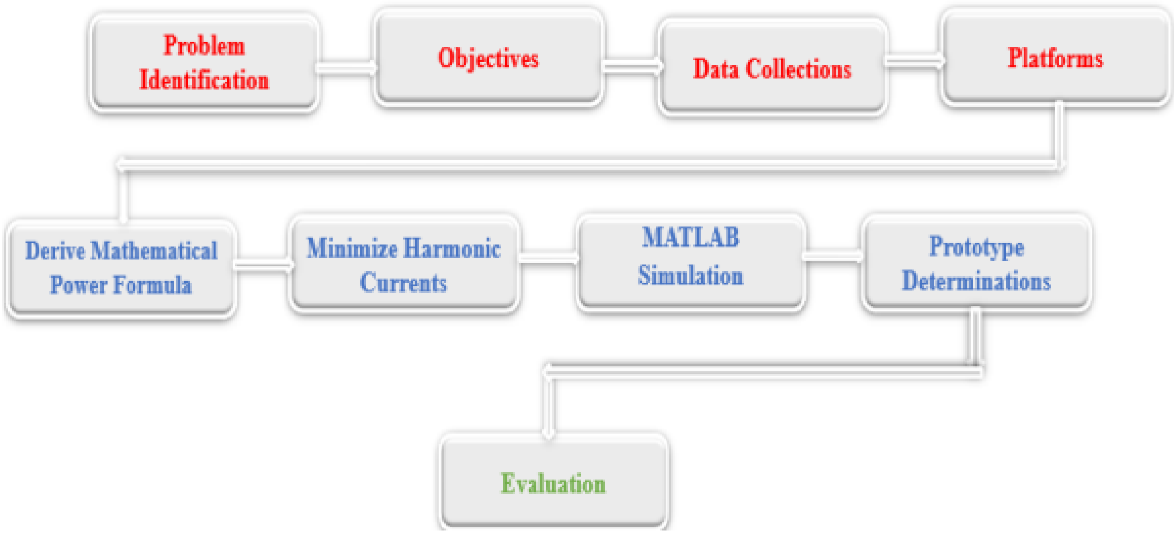

Fig. 1.8: Methodological diagram of project

1.3.7: Building assignment

The following diagram shows the structure of the project.

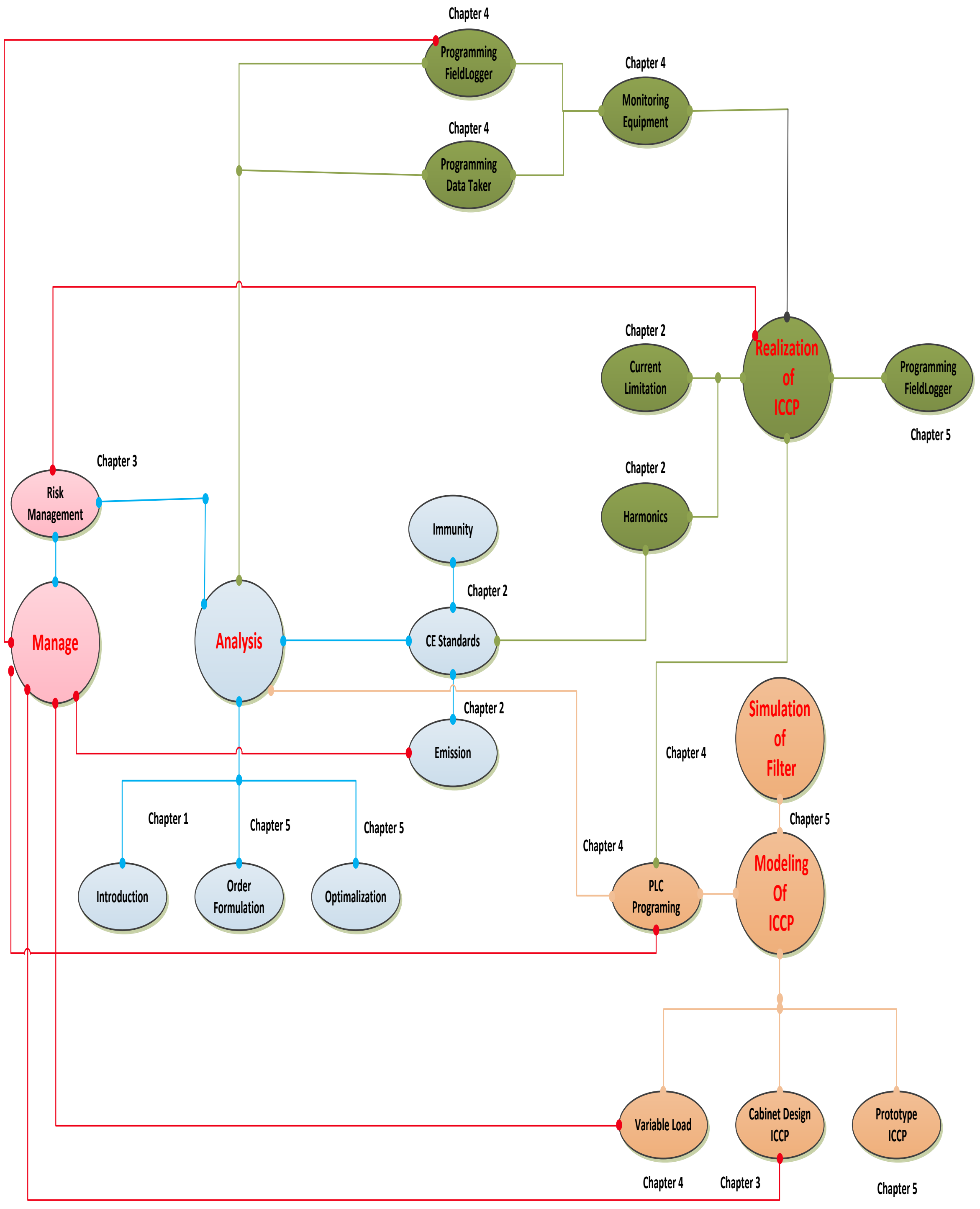

Fig. 1.9: Structure diagram of project

2. CE standards for a prototype ICCP

2.1: Introduction

During the design of the measurement and control cabinet, the research is carried out to determine whether it complies with the CE / IEC regulations. The MME has three standards, they are: immunity, emission and harmonic. These three standards are initially examined. Then an advice is sought on which standards belong to immunity, emission and harmonic.

Standards IEC 61000-6-2 and IEC 61000-6-4 were chosen on the basis of advice given by the DARE organization [5]. This provides advice on immunity and emission. DARE Instruments also uses other brand names such as EM Field and Radio Field.

Then it is determined what the limit values are and how the measurement methods will be used. It is initially checked whether the immunity, the emission and the harmonic comply with the CE / IEC standards. Then the general limit values are determined, the measurement methods as well.

The CE test results of the immunity and emission are already in the Datasheet of HWS. The manufacturer did not provide any data about the harmonic standard and that had to be measured during the graduation internship. If the test is carried out, it is very expensive. The data from the HWS data sheet is reliable, so that it could immediately be used. The current harmonic test is a very comprehensive test, and it is separately described in chapter 5.

2.2: Immunity

EMC stands for Electromagnetic Compatibility. EMC tells how equipment behaves in relation to the electromagnetic environment, to what extent one equipment affects another or vice versa. Immunity is the degree to which a device is resistant to electromagnetic radiation.

Typical sources include, for example, power lines, electronic circuits, electric motors, radio and radar transmitters. Equipment that is being disrupted, often referred to as 'victim' equipment by the EMC specialists, it can consist of almost anything that uses EM energy, such as radio receivers, household appliances or electronic circuits of any kind. On the immunity side, the purpose is to ensure that the equipment is not affected by, for example, radio transmissions, power supply disturbances, electrostatic fields or other phenomena.

2.2.1: Immunity Standards

Standard IEC 61000-6-3

This part of IEC 61000 for immunity requirements EMC applies to electrical and electronic equipment used in industrial environments. Immunity requirements in the frequency range from 0 Hz to 400 GHz are included [6]. (For details, see Appendix B- Immunity Standard)

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[5] http://www.dare.nl/informatie/organisatie

[6] NEN-EN-IEC 61000-6-3: en, fr, Elektromagnetische compatibiliteit (EMC) - Deel 6-3: Algemene normen - Immuniteit voor industriële omgevingen, 2006

<table>
<tr><th></th><th>Environmental phenomena</th><th colspan="2">Test specification</th><th>Units</th><th>Basic standards</th></tr>
<tr><td>4.1</td><td>Radio-frequency
common mode</td><td colspan="2">0.15 to 80
10
80</td><td>MHZ
V
% AM (1KHZ)</td><td>IEC 61000-4-6</td></tr>
<tr><td rowspan="2">4.3</td><td rowspan="2">Voltage dips</td><td colspan="2">0
1</td><td>% Residual voltage
cycle
Cycle</td><td rowspan="2">IEC 61000-4-
11</td></tr>
<tr><td>40
10/12
At 50/60Hz</td><td>70
25/30
At
50/60Hz</td><td>% Residual voltage
Cycle</td></tr>
<tr><td>4.3</td><td>Voltage
interruptions</td><td colspan="2">0
350/300 at 50/60Hz</td><td>% Residual voltage
Cycle</td><td>IEC 61000-411</td></tr>
<tr><td>4.4</td><td>Surges
line-to-earth
line-to-line</td><td colspan="2">1 .3/50 (8/30)
±2
±1</td><td>Tr/Th µs
KV (open circuit
test voltage)
KV (open circuit
test voltage)</td><td>IEC 61000-4-5</td></tr>
<tr><td>4.5</td><td>Fast transients</td><td colspan="2">±2
5/50
5</td><td>KV (open circuit
test voltage)
Tr/Th ns
Repetition
frequency kHz</td><td>IEC 61000-4-4</td></tr>
</table>

Table 2.1: The immunity limits according to IEC 61000-6-3

2.2.2: Limits

Table 3.1 shows the maximum immunity limits according to IEC 61000-6-3 for five environmental phenomena:

1) Radio frequency common mode
2) Voltage dips
3) Voltage Interruptions
4) Overvoltage (line-ground and line-line)
5) Fast transients

2.2.3: Evaluation against limit values

The most important part of the system, the converter, has already been tested by HWS. The other parts (for example the current regulator and the sensor) are not connected to the input voltage. So, they have no influence on this.

For radio frequency common mode Noise in a cable, or transmitted from a cable, usually occurs in common mode, i.e., the same signal is likely to be picked up by both conductors in a two-core cable for 0.15MHz to 80MHz. The IEC 61000-4-6 standard is used in radio frequency test.

Electrical and electronic equipment can be affected by voltage dips from the power supply. Voltage dips are caused by faults in the network or by a sudden large change in the load.

The electrical and electronic equipment can be affected by short interruptions to the power supply. Errors in the network or a sudden large change in the load cause interruptions. The IEC 61000-4-6 standard is used in voltage dips and voltage interruptions tests. The purpose of overvoltage test is to find the response of the DUT in overvoltage operating conditions, and when switching effects occur at certain imminent levels. The IEC 61000-4-5 standard is used in radio frequency test.

The repetitive fast transient test is a burst test which consists of multiple fast transients coupled into the power, control, and signal ports of electrical and electronic equipment. The IEC 61000-4-4 standard is used in radio frequency test.

2.2.4: Sub- conclusion immunity

The results are within the limits of the standard. These tests do not need to be repeated. The system thus meets the immunity standard.

2.3: Emission

EM emission is the disturbance of equipment that is sensitive to it. EM disturbances can work in more than one direction. Disrupting more than one device, or multiple sources, has a cumulative effect on a single piece of equipment. For example, air traffic control radar can affect the display of a laptop computer used on an aircraft, as well as other vital devices in use on the ground. At the same time, the emissions from the same laptop computer can converge with those from mobile phone systems, disrupting the systems in the aircraft.

2.3.1: Emission Standard

Standard IEC 61000-6-4

This part of IEC 61000 for emission regulations EMC applies to electrical and electronic equipment used in industrial environments. Emission requirements in the frequency range from 0 Hz to 400 GHz are included [7]. (See Appendix C - Emission standard)

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7 NEN-EN-IEC 61000-6-4: en Elektromagnetische compatibiliteit (EMC) - Deel 6-4: Algemene normen - Emissienorm voor industriële omgevingen, 2011

Port	Frequency range	Limits	Basic standard
1) Enclosure port	30 MHz-230 MHz 330MHz-000MHz	40 dB(uv/m) Quasi-peak at 10 m 47 dB(uv/m) Quasi-peak at 10 m	CISPR 16-3-3
3) Low voltage AC mains port	0,15 MHz-0,5MHz	79 dB(uv)quasi-peak 66 dB(uv)quasi-peak	CISPR 16-3-1, 7.4.1 CISPR 16-1-3, 4.3
	0,5MHz-30MHz	73 dB(uv)quasi-peak 60 dB(uv)average	
3) Telecommunications/ Network port	0,15 MHz-0,5MHz	97 dB(uv)- 87 dB(uv)Quasi-peak 84 dB(uv)- 74 dB(uv) average 53 dB(uA)- 43 dB(uA)Quasi-peak 40dB(uA)-30 dB(uA) average	CISPR 22
	0,5MHz-30MHz	87 dB(uv)quasi-peak 74dB(uv)average 43 dB(uA)quasi-peak 30dB(uA)average	

Table 2.2: Maximum emission limits

2.3.2: Limits

Table 2.3 shows the maximum emission limits according to IEC 61000-6-4 for three ports.

1) **Enclosure port**

This refers to the EM radiation that radiates through the cover of the device. Considering an earthed metal cover, it is expected that this EM radiation (> 30MHz) always falls within the standard.

2) **Low voltage AC port**

This refers to the EM radiation through the power cable. This certainly applies, because a power cable is used. Test results are available for the TDK-HWS voltage converters.

- **Limits for frequency 0.15-0.5 MHz**

Standard: Standard CISPR 16-3-1 [8]

Limit value quasi peak: 79 dB (uV)

Limit value average: 66 dB (uV)

- **Limits for frequency 0.5-30 MHz**

Standard: CISPR 16-1-3 standard [9]

Limit value quasi peak: 73 dB (uV)

Limit value average: 60 dB (uV)

3) **Telecommunication/network port**

This applies to EM radiation on the Ethernet port of this system. Since this is a standardized Ethernet controller, which is checked the standard software and because a shielded cable is also used, it is expected that the EM radiation will always fall within the standard.

2.3.3: Evaluation against limit values

In the enclosure port is meant the EM radiation that radiates through the housing of the device.
Since it concerns with an earthed metal housing, it is expected that this EM radiation (> 30MHz) always falls within the standard.
In low voltage AC port, the EM radiation is meant by the power cable. This certainly applies, because a power cable is used. Test results are available for the TDK-HWS voltage converters. Network port applies to EM radiation on the Ethernet port of this system. Since this is a standardized Ethernet controller, which is controlled with standard software and because a shielded cable is used as well, it is expected that the EM radiation will always fall within the standard. The measuring method according to standard CISPR 16-1-3 is made. Measuring disturbances conducted along cables is known. When testing for compliance with emission limits for electromagnetic disturbances is conducted along cables, some items will be considered minimum. There are two methods of measuring conducted disturbances, either as voltage or as current. Both methods can be used to measure the three types of conducted disturbances.
They are: the common mode voltage, the common mode current and the asymmetric mode voltage. The type of measuring equipment is chosen to determine the fault characteristics (voltage and current probe). Regarding the low voltage AC mains port for HWS 1500 the frequencies are between 15 MHz-0.5MHz the limits are 79 dB and 66 dB, and for HWS 1000 are between 30 and 38 db. See Appendix C - Emission standard to test the emission from the low voltage port, certain devices must be available, such as a frequency meter (equalizer).

2.3.4: Sub-conclusion Emission

According to the rectifiers provide these special devices which satisfy the emissions test.

---

[8] CISPR 16-2-1: en Specificatie voor meetontvangers en meetmethoden voor radiostoringen en -immuniteit - Deel 2-1: Methode voor het meten van storingen en immuniteit - Geleide storingsmetingen, 2010

[9] CISPR 16-1-2: en Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-2: Radio disturbance and immunity measuring apparatus - Coupling devices for conducted disturbance measurements (Redline version with track changes), 2014

2.4: Harmonic

An electrical system supplies power to loads by supplying current at the fundamental frequency. Only fundamental frequency current can deliver real current. Current delivered at harmonic frequencies cannot deliver real power to the load. Power systems are designed to operate at a frequency of 50 or 60 Hz. However, certain types of charges produce currents and voltages with frequencies multiples of the 50 or 60 Hz fundamental frequency. These higher frequencies are known as power system harmonic.

2.4.1: Harmonic standard

IEC 61000-3-2 deals with the limitation of harmonic currents which is injected into the public grid system. It specifies limits of harmonic components of the input current that can be produced by equipment and it has been tested under specified conditions. It applies to electrical and electronic equipment with an input current of up to 16 A per phase and it intended for connection to public low-voltage distribution network systems. See Appendix D- Harmonic standard.

2.4.2: Limits

There are several classes for the boundary of the harmonic. See the following figure:

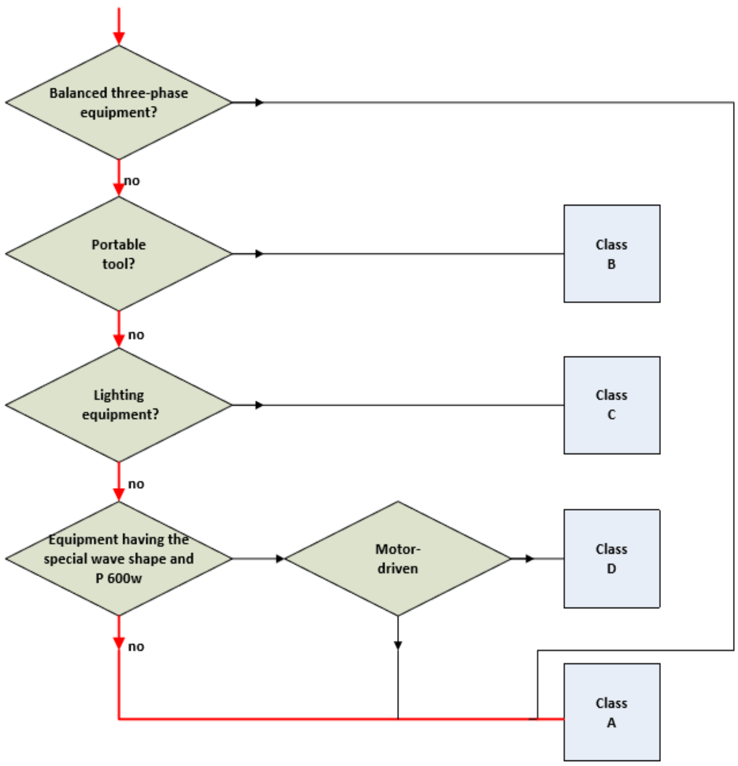


Fig. 2.1: Determine the scheme for the class

On the account of the system is not connected to the public low-voltage grid, this standard does not strictly apply. If the low-voltage grid could be connected to it later, this standard does apply. According to the flow chart, class A would apply. In the standards for appliances, requirements are set for the harmonic currents that may be present in the current drawn from an appliance. Table 2.3 gives an example of the maximum harmonic currents in a device up to a nominal current of 16 A. [10]

---

[10] **Compliance Testing to the IEC 61000-3-3 (EN 61000-3-2) and IEC 1000-3-3 (EN 61000-3-3) Standards**

Harmonic (n)	Maximum harmonic current
Odd harmonic	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
15<n<39(n=Odd)	0.15*(15/n)
Even harmonic	
3	1.08
4	0.43
6	0.30
8<n<40(n=even)	0.23*(8/n)

Table 2.3: Maximum harmonic currents device 16A

2.4.3: Testing against limits

The manufacturer did not provide any information about this and this had to be measured during the graduation internship. This is a very extensive test, and it is separately described.

2.4.4: Sub- conclusion Harmonic

The results show compliance with IEC 61000-3-2.

3: A prototype of ICCP

In this chapter a brief idea will be given to design a practical model of ICCP. As a result of study, analysis and accumulated experience, this model was presented. On this model, analysis, modeling, and simulation took place. The components have so far already been selected. However, the relationships had not yet been established. All components are discussed in this chapter. The final result of this is the wiring diagram used to build a prototype system.

Finally, and as a principle it is discussed how the flow controller works and a risk analysis is executed with regard to the age assumption.

3.1: Modelization

In order to the components have to work together: that requires an elaboration in details. The electrical diagram should be designed. As shown below is the general block diagram of the cathodic protection system measurement and control cabinet:

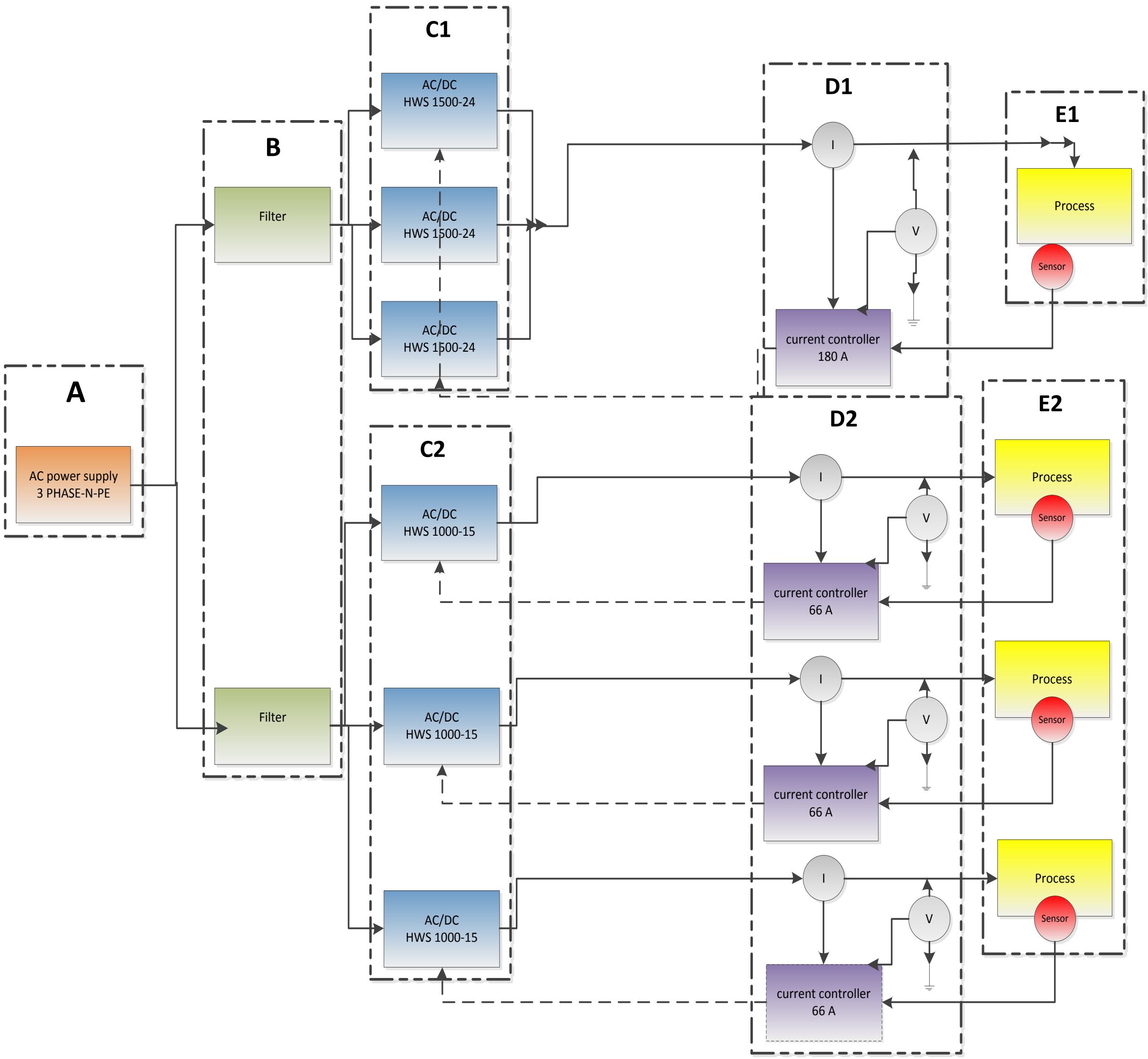


Fig. 3.1: Electrical diagram of measuring and control box of ICCP

3.2: Hardware components

A. AC power supply (input)

B. Filter

C. TDK-HWS AC/ DC converters

C1. 3xTDK-HWS AC/DC inverters (TDK-HWS 1500-24)

C2. 3xTDK-HWS AC/DC inverters (TDK-HWS 1000)

D. 4x Current controller

***D1. 1x Current* controller**

***D2. 3x Current* controller**

E. Power outputs (output)

E1. First exit

E2. Second exit

F. Other (PCB)

A. AC supply Input:

Input: AC - Power Supply = 400V (line-line). 230V (phase neutral)

Frequency = 50 Hz

Input current = 16A (3 phase)

B. Filter

First it must be determined which filter is needed and which calculations have to be made. Then it must be designed.

C. TDK-HWS AC/DC inverters

TDK-HWS-HWS1500-24 and TDK-HWS-HWS1000-15 are used as supply voltages for this system.

- **The Front Side of TDK-HWS AC/DC**

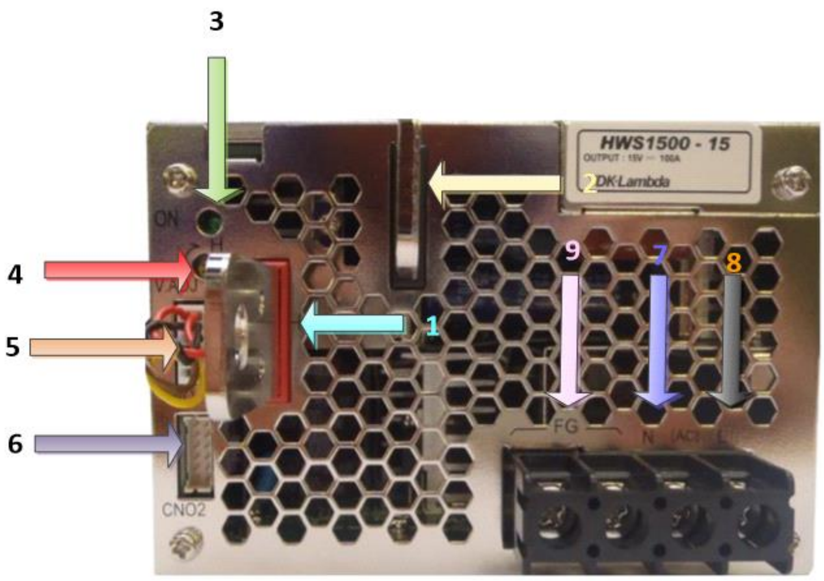


Fig. 3.2: The front cover of TDK-HWS

Explanation of the numbers:

1. +: positive end point
2. -: negative end point
3. ON: device on (LED)
4. V.ADJ: fine regulator output voltage
5. CN1: remote sensor, on / off control signal, current balance signal, power lack signal, output voltage external control signal
6. CN2: As stated above
7. AC input terminus N: neutral line
8. AC input end point L: phase line
9. FG: Earth endpoint

- *CN1, CN2 connector pin configuration and function*

CN1 and CN2 have the same pin configuration and function. They are interconnected in TDK-HWS power supply. [11]

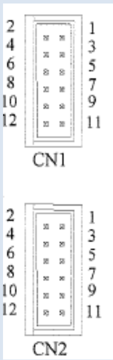
	Pin no.	Config.	Functie
	**1**	**+Vm**	Endpoint access screen. Connected to + output endpoints
	2	**+S**	Remote sensing end point + output (For the remote sensing function, which compensates for the weakening line between the power supply and the load. + S connected to the + Vm, when the remote sensing function is unnecessary)
	3	**-Vm**	Endpoint screen. Connected to - output endpoints
	4	**-S**	Remote sensing end point - exit (For the remote sensing function, which compensates for the attenuating line between the power supply and the load. -S connected to the - Vm, when the remote sensing function is unnecessary)
	5	**PC**	End point current balance (For output current balance in parallel operation).
	6	**COM**	GND for PC and PV signals.
	7	**PV**	Output voltage external control end point. (For power supply output voltage control with an external voltage)
	8	**NC**	No connection
	9	**CNT**	Remote ON / OFF control end point. (Power ON / OFF control with an external signal)
	10	**TOG**	GND for CNT and PF signals, just like Pin 12
	11	**PF**	Power supply error signal (PF signal) output. (If the output voltage drops, or the fan stops and AC input voltage goes down, the power supply fault limit will go up).
	12	**TOG**	GND for CNT and PF signals, just like Pin 10

Table 3.1: Explanation numbers of TDK-HWS

[11] **HWS 1500 Series- Instruction Manual- Densi-Lambda-2009**

C1. 3xTDK-HWS AC/DC inverters (TDK-HWS-HWS1500-24)

A 180 A is required for the first AC / DC converters (TDK-HWS-HWS1500-24). So, the connection of the three types of power supply should be parallel. To increase the current of the output, the following way should be used:

- PC to PC (the current balance end point for the output current balance in parallel operation)
- COM to COM
- The current balance function activates and the output current of each power supply is supplied in equivalent to the load

Wires at the PC endpoints, the COM endpoints should be very short and twisted and have the same length. See figure 2.3:

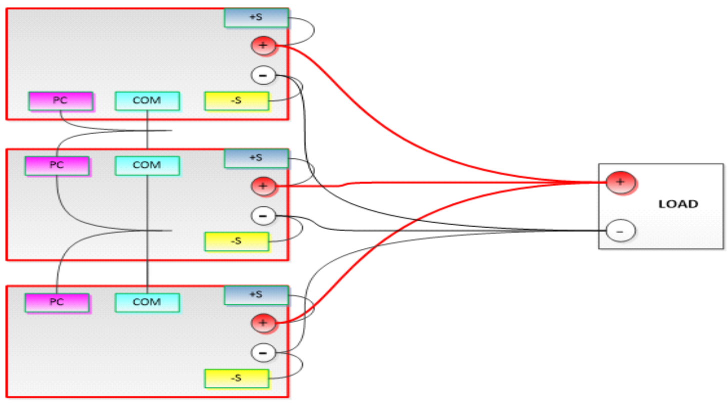


Fig. 3.3: Connected parallel AC / DC converters

C2. 3xTDK-HWS AC / DC converters (TDK-HWS-HWS1000-15)

Three times of 66A TDK-HWS-HWS1000-15 are required for the second supply voltage, so each supply should be separately used. The way of the output voltage external control is used in the following way:

- There has to be a voltage output for the external monitoring function.
- The voltage output can vary by applying an external voltage of (1 - 6V) for the PV end point and for the COM end point.
- If external voltage is not used, there will be no output. See figure 3.4:

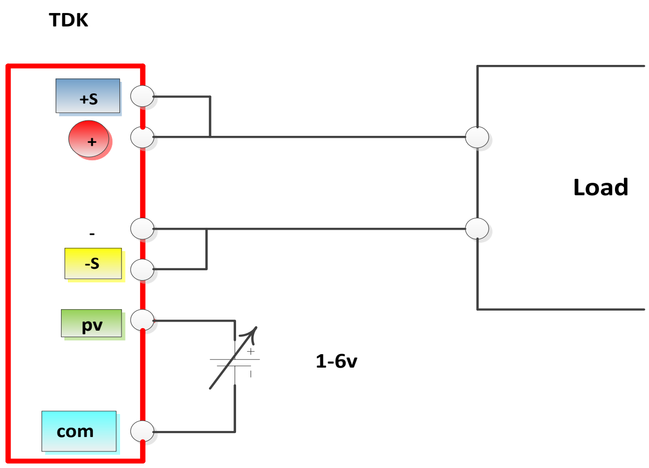


Fig. 3.4: Connection of the output voltage to external control

According to the linear method, only for the 5-36V output model, the output voltage of 20% to 120% is used at the PV voltage of 1V to 6V.

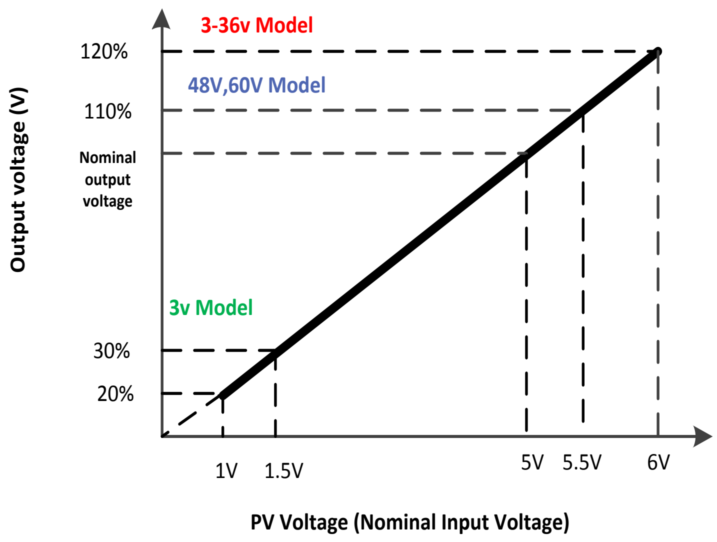


Fig. 3.5: Linear output against the PV voltage

D. Current controller

One power regulator sends power to one AC / DC converters or one power regulator sends power to three AC / DC converters coupled in parallel. The sensor signal is compared with the other signal (set point) by the operational amplifier. The result of high or low is passed on to the PV of the AC / DC inverters. See figure 3.6:

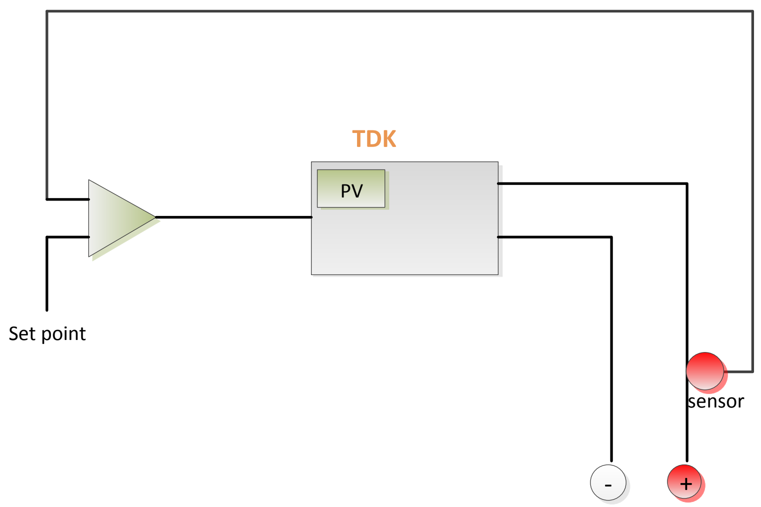


Fig. 3.6: Flow regulator

D1. 1x Power regulator

- 1 current regulator (DCM) is used
- The current controller (DCM) is connected in parallel to the 3x AC/ DC converters (TDK-HWS 1500-24).

D2. 3x Power regulator

- There is current controller (DCM) is X3 used.
- Each current controller (DCM) is coupled with AC / DC converters (TDK-HWS1500-15).

E. Power outputs (connections to the load)

E1. First output

- Output DC voltage (3xTDK-HWS-HWS1500-24) = 24 V
- Output current (maximum) = 65 A (per device)
- Output power (maximum) = 1650 W (per device)
- Together: 3x approximately 60 A = 180 A.

E2. Second output:

- Output dc-voltage (1xTDK-HWS-HWS1000-15) = 15 V.
- Output current (maximum) = 70 A (per device)
- Output power (maximum) = 1050 W (per device)

E3. second output:

- Output DC voltage (1xTDK-HWS-HWS1000-15) = 15 V.
- Output current (maximum) = 70 A (per device)
- Output power (maximum) = 1050 W (per device)

E4. Second output:

- Output DC voltage (1xTDK-HWS-HWS1000-15) = 15 V.
- Output current (maximum) = 70 A (per device)
- Output power (maximum) = 1050 W (per device)

3.3: Scheme measurement and control box

3.3.1: Main converter

See figure 2.7. (See the complete diagram in Appendix E-Electrical Schematic)

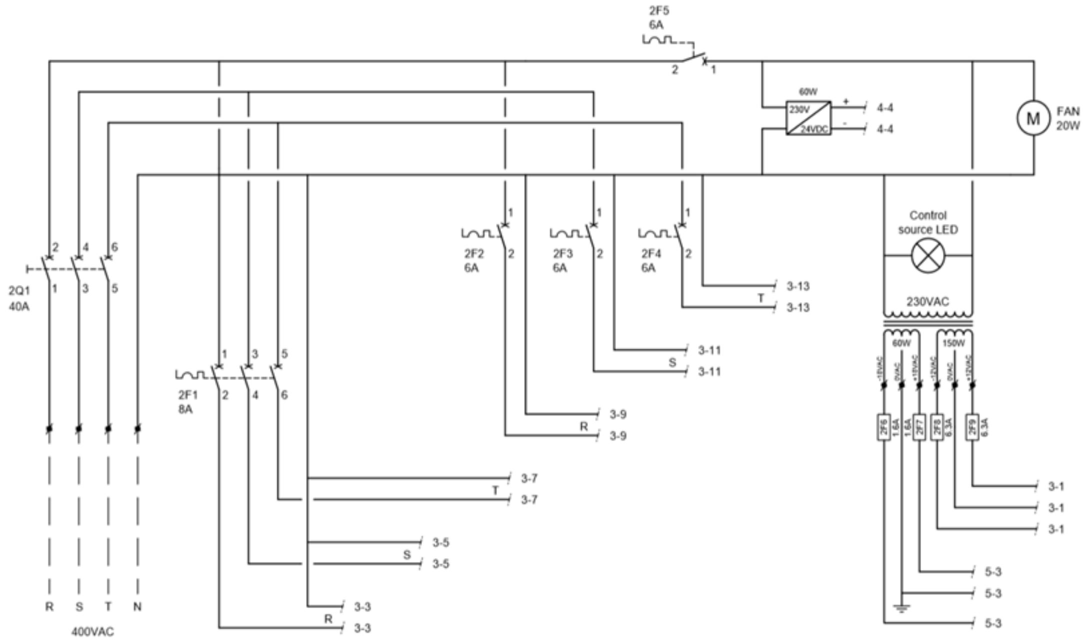


Fig. 3.7: Main Power

3.3.2: TDK-HWS controller

The power controller sends power to the TDK-HWS1500-24 (No. 1,2,3). The connection between the two devices is called LME on the flow controller and CN on the TDK-HWS-HWS. The last three flow controllers each operate one TDK-HWS-HWS. See flow regulator.

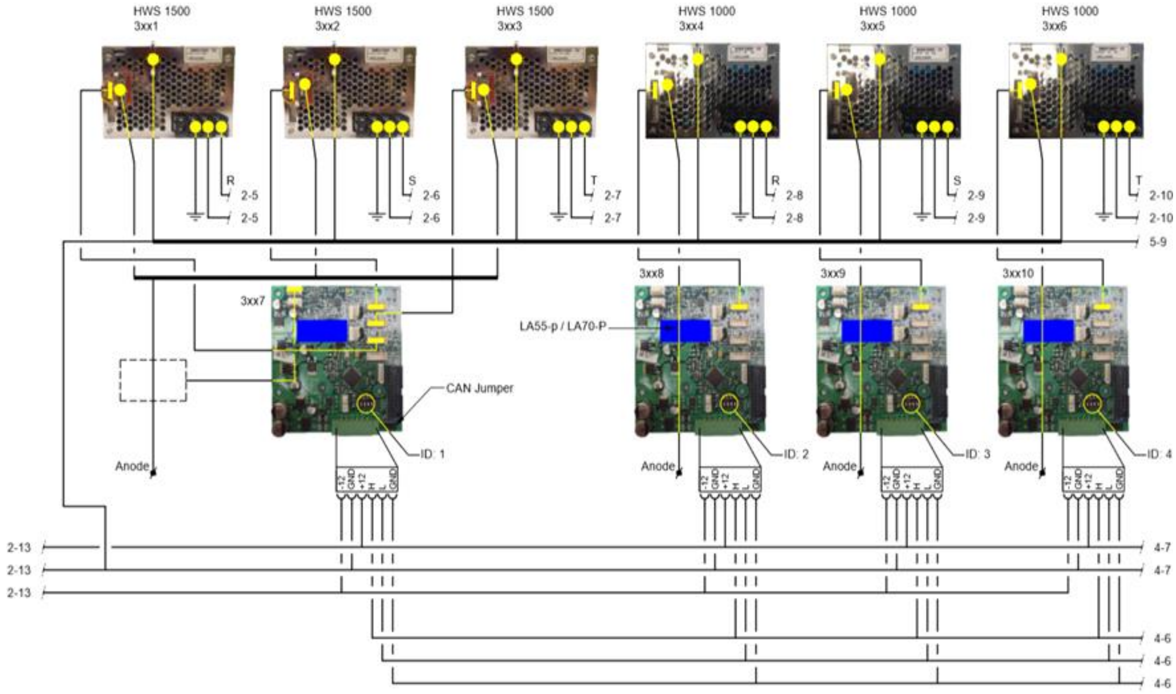


Fig. 3.8: TDK-HWS controller

3.4: Risk management

Risk management has been used in this project. All possible risks are described here. With the help of this document, decisions can be made to reduce or eliminate risks.

Each risk has two separate values. They are the probability and the impact values.

Probability is a criterion of the risks to be encountered.

- Probability = 1. Probability of this risk happening: is small
- Probability = 2. Probability of this risk happening: is moderate
- Probability = 3. Probability of this risk happening's big

Impact is the measurement of the consequences to be encountered.

- Impact = 1. If the above risk occurs, the impact is: small
- Impact = 2. If the above risk occurs, the impact is: moderate
- Impact = 3. If the above risk occurs, the impact is: big

This is visualized as follows in the tolerance matrix below.

Impact				
Big	3	6	9	
Moderate	2	4	6	
Small	1	2	3	
	Small	**Moderate**	**Big**	**Possibility**

Table 3.2: Tolerance Matrix

The tolerance matrix for the measurement and control cabinet looks like this:

Components	Expected life age (years)	Probability	Impact	Final result	Remark
TDK-HWS-HWS	5	1	2	2	**Moderate**
Motherboard	10 till 25	1	2	2	**Moderate**
Flow regulator	10 till 25	1	2	2	**Moderate**
Transformer	15 till 35	2	2	4	**Moderate**
Fan	5	3	2	6	**Moderate**

Table 3.3: Tolerance Matrix of measurement and control cabinet

3.5: Lifetime

The TDK-HWS is warranted for a period of 5 years from the date of shipment. If the distribution fails under normal use during the warranty period (5 years), then the repair is free.

The conditions of the warranty are:

1. Average operating temperature (ambient temperature of the power supply unit is less than 40 C0).
2. Average load factor is 80% or less.

The life age of the measurement and control box is approximately 25 years, but the fans have a life age of only 5 years. They must be replaced within five years.

4: Test setup for ICCP

4.1: Introduction

Tests have been performed to determine that the cabinet complies with the harmonic standard and to define the current limit. That is why a test set-up should be done.

Before the test begins, preparations must be carried out for the measuring equipment (the FieldLogger and the Data Taker), it must be set up for suitable measuring methods for a test. There should also be a test set-up to be made and it is programmed in advance for the variable load and the PLC.

In this chapter the principle of the scheme of the Test Setup is drawn. Then the test setup of the measuring equipment is programmed, so-called the FieldLogger (test 1), the Datalogger (test 2 to 6).

This section discusses which measures have been taken to increase the measurement resolution via the PLC (experiments 1 to 6).

According to the variable load test arrangement, a variable load resistor is required. This should first be analysed, then the value of the variable load resistor per lamp must be calculated. A design is needed, even as its optimization.

4.2: Block diagram

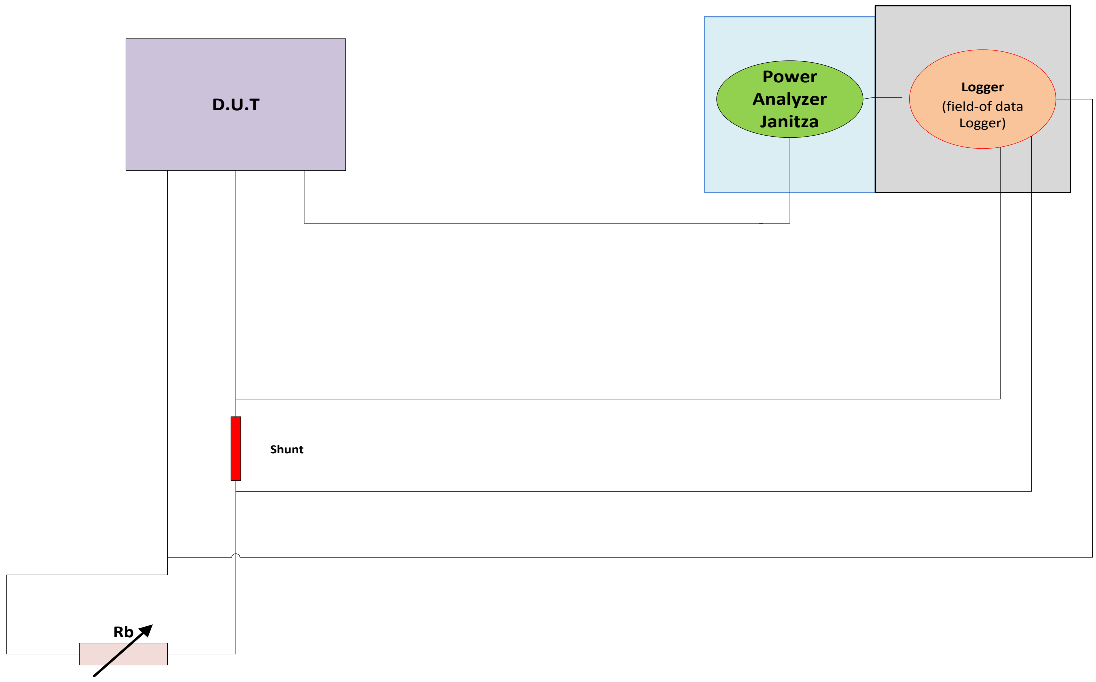


Fig. 4.1: Block diagram for ICCP

4.3: Preparation of measurements (hardware and software)

4.3.1: Programming the FieldLogger

The FieldLogger is a high-resolution and high-speed data acquisition and logging equipment for analog and digital signals. The main features are: [12]

- Analog inputs: 8
- Digital inputs/ outputs: 8
- Relay outputs: 3
- 3 MB of internal memory
- SD card interface (up to 16 GB - not available in some models)
- RS485-interface

[12] FieldLogger, Instruction manual, Novus

Fig. 4.2: Front panel of the FieldLogger

The FieldLogger has two rows of connectors for various connections; below are the following items: Ethernet, inputs, power supply, output relays, external power output, digital inputs and serial communication. See fig.4.3:

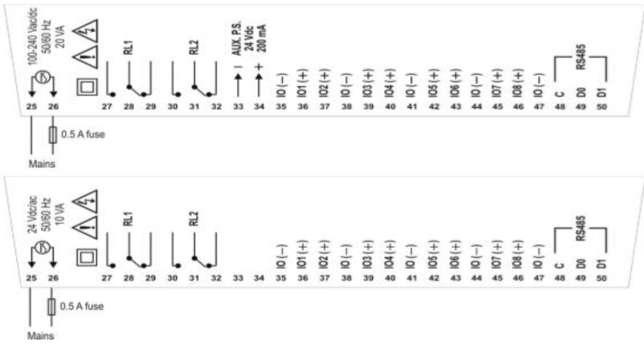


Fig. 4.3: Top connections of the FieldLogger

And the bottom connections of the FieldLogger are shown below:

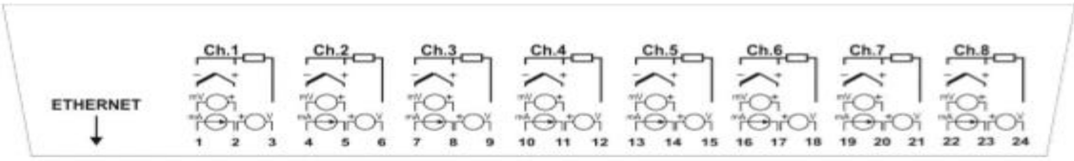


Fig. 4.4: The bottom connections of the FieldLogger

The Field Logger's RS485 interface has connections for the 3 connections, including the common (ground). The connection in a Modbus network hangs if the device is configured to work as master or slave. In this test1 the device is master.

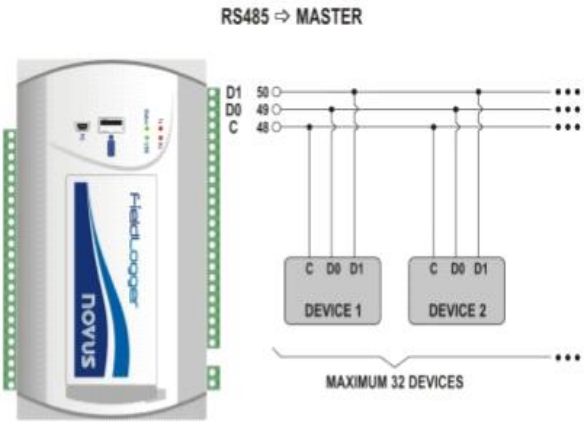


Fig. 4.5: RS485 as master

The device has 8 analog inputs, of which 1 input is used for measuring the output current (mV) and the 3nd for measuring the output voltage (0-10V). Note the correct polarity of the connection.

Voltage (mV) Output voltage (0-10 V)

Fig. 4.6: Analog Inputs - Connection

On the RS485 interface screen one chooses the behaviour of the interface as Modbus RTU Master. When the interface is used as a slave, the Modbus address, baud rate, parity and number of stop bits has to be configured. When the interface is used as master, the Modbus address does not need to be configured. In addition, in this case the configuration of the Modbus network, which states what work is done by slaves, can be read on the Remote Channels screen.

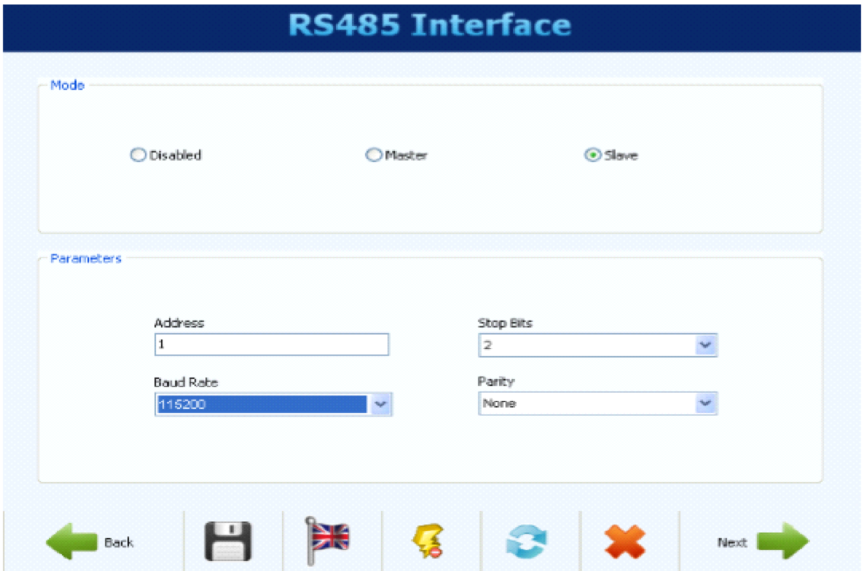


Fig 4.7: RS485 interface

Each channel should be individually configured. First you select which channel in the list (left) you should set. For each channel a tag (name with 16 characters max) must be configured and an input type. Depending on the selected input type, prompt limits must be set. There are two analog channels for output current [A] and output voltage [V].

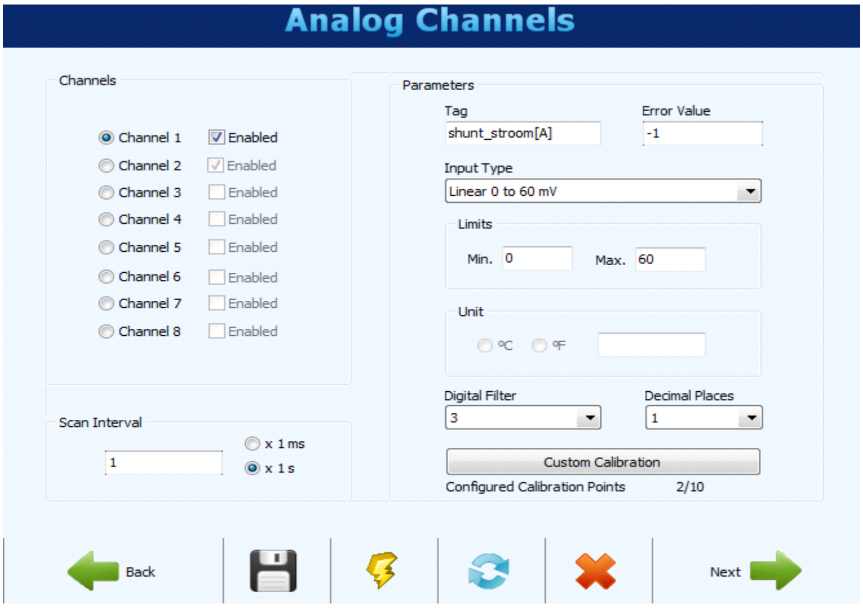


Fig. 4.8: Analog Channels Configuration- shunt current

For the output voltage is:

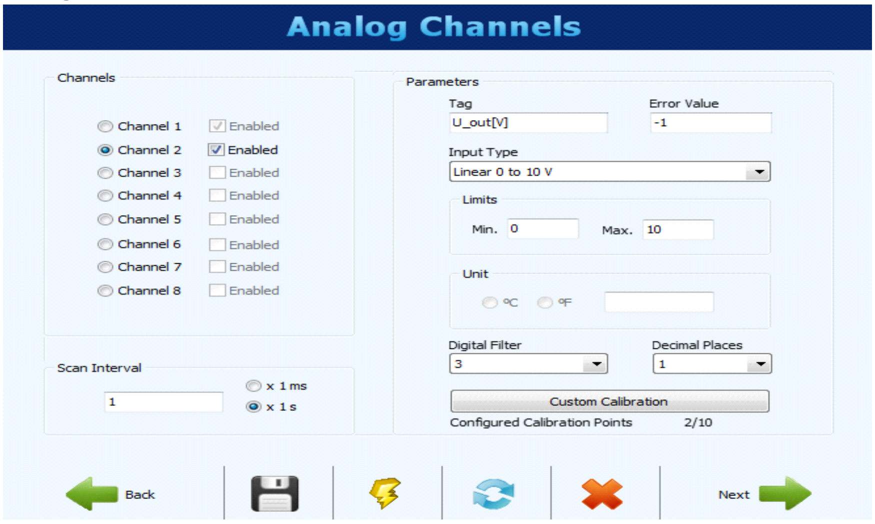


Fig. 4.9: Analog Channels Configuration- Output Voltage

With the "Custom Calibration" button, up to 10 calibration points can be set for each analog channel.

- Select channel to set.
- Fill in 1st default value and 1st FieldLogger Value
- Click on add and enter 3nd default value and 3nd FieldLogger value. etc.
- For the output current, 60 mv is equal to 300 Am.

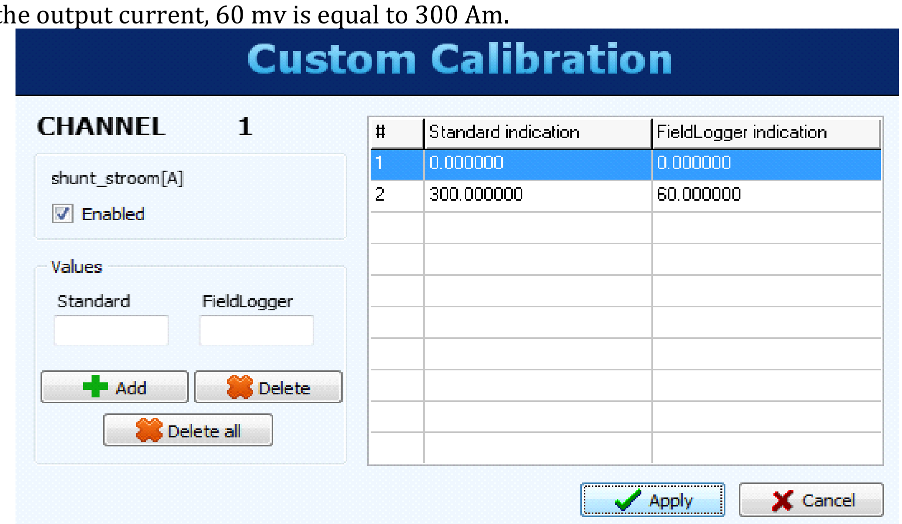


Fig. 4.10: Custom Calibration - for the output current

And for the output voltage, 10V is equal to 20V.

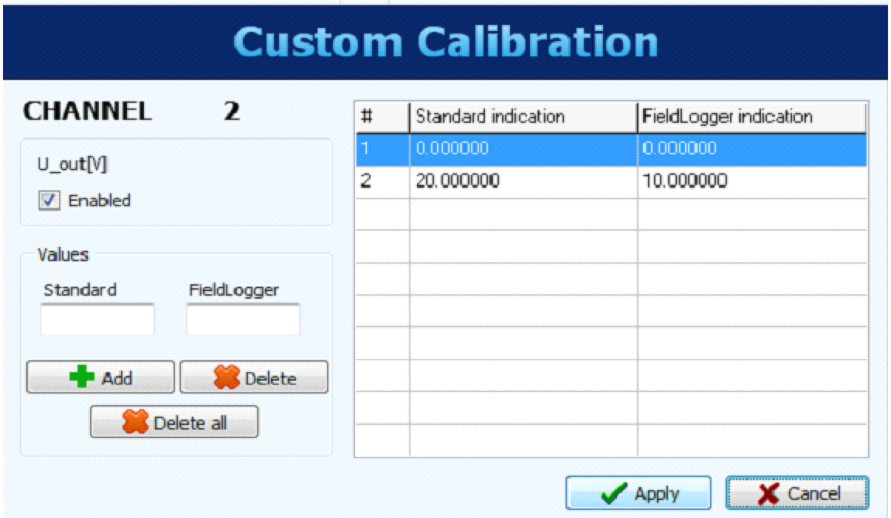


Fig. 4.11: Custom Calibration – for the output voltage

If the RS485 interface is configured as Modbus master, the following screen appears. Enter a tag that is unique to each channel. Set for each channel which network to read as slave, which Modbus command to use and which initial register to read as slave.

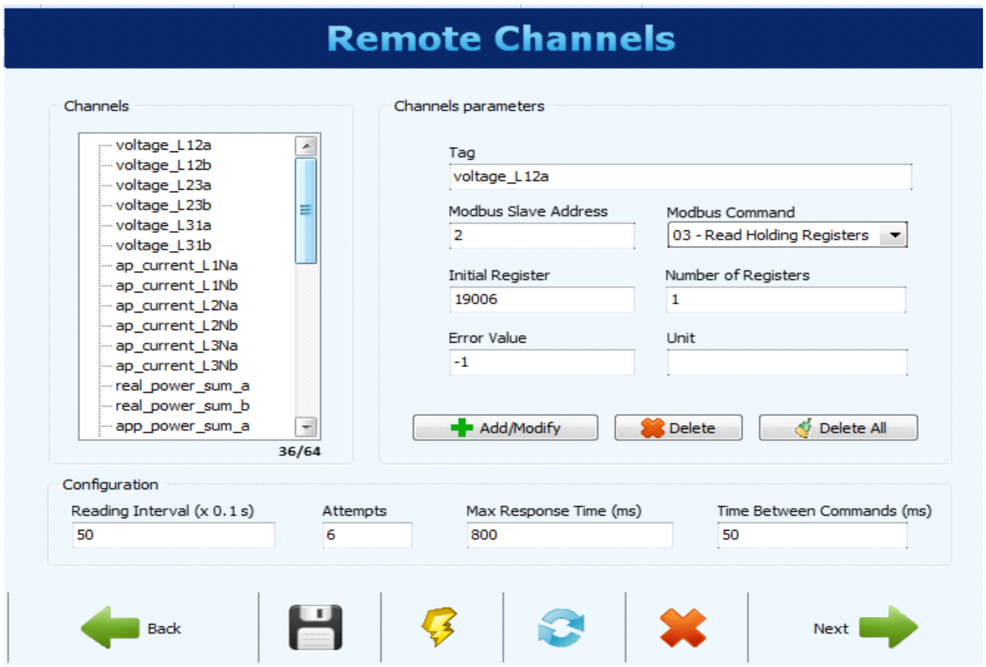


Fig. 4.12: Remote channel

The next screen shows the configuration of the virtual channels. Each virtual channel is the result of an arithmetic/logical operation, which must be modified by means of a unique label (name of 16 characters max) for each channel. Select the first channel as the operand. Select "constant value", so that a numerical value is assigned to the virtual channel. This value is used as an operand in other virtual channels. Then determine in the same way which channel will be chosen as the second operand.

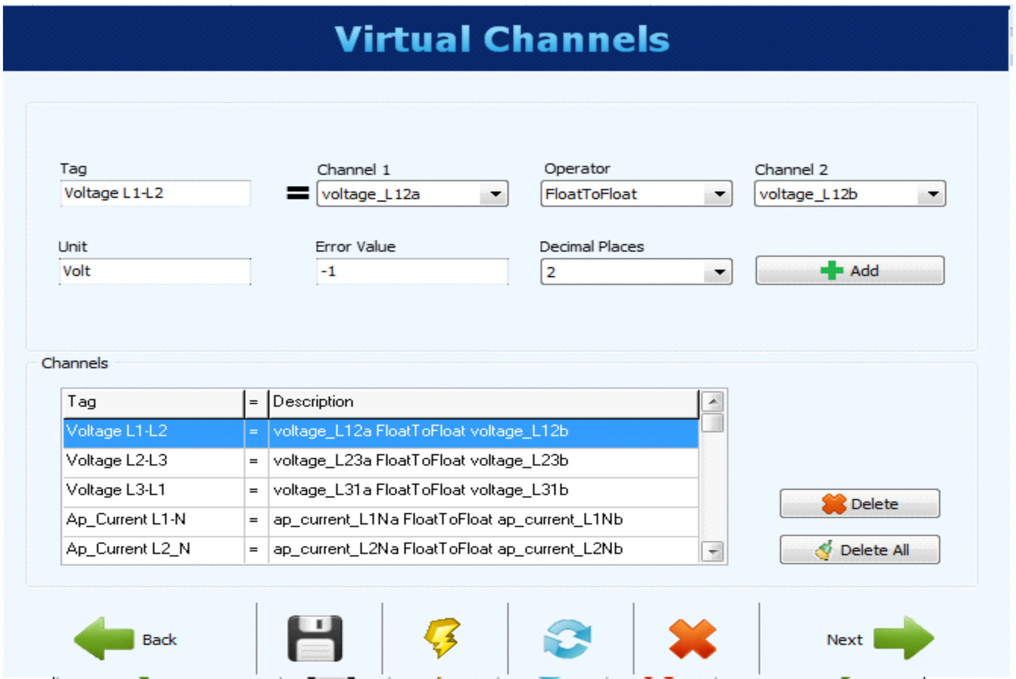


Fig. 4.13: Virtual channels

4.3.2: Programming the Data Taker DT80

The FieldLogger is started to read the data from the power analysis. The FieldLogger has a maximum of 33 channels with a 33-bit register (float to float). Since this is not sufficient for reading the data of all variables, one has to resort to the Data Taker 80, which has 356 channels and works more accurately. Then you have to program. The Data Taker is in the next test master. [13]

DT80 Modbus Master

Modbus is a simple communication protocol widely used in SCADA (supervisory control and data acquisition) systems. Modbus provides an efficient and standardized way to transfer digital states and data values between a RTU (remote terminal unit), a programmable logic controller (PLC) and a supervising computer.

In a Modbus-based SCADA system, each RTU/PLC acts as a Modbus server or slave. These servers obey orders of the Modbus and respond to requests from a Modbus client, or master system. A Modbus client is usually a computer that has a dummy display, a user interface and various data logging and alarm functions.

Modbus related profile settings

Serial Sensor Port:

PROFILE SERSEN_PORT FUNCTION = mode

PROFILE SERSEN_PORT FLOW = NOFC

PROFILE MODBUS_SERVER SERSEN_ADDRESS = addr

The mode can be:

- Modbus - for Modbus slave mode
- Modbus -Master - for Modbus Master mode
- Addr 8 bits Modbus slave address in the range of 1-247.

nMODBUS Channel Type

The DT80 uses the Modbus cable type to read or write the registers of the Modbus slave devices. The channel options provide the register address, data types, etc.

nMODBUS (options) = value

The mode can be:

- n = the Modbus master port of the command will be sent (see table)
- Options = the data Taker channel options

Port Number *n*	Physical connection
1	Serial sensor port
2	Host port
4	Ethernet port

Table. 4.1: nMODBUS Channel Type

Data Type/ Format (MBxx)

- xx = the type of data:
- I = 16 bits in total (default)
- V = 16 bits unsigned number
- L = 33-bit integer transferred using two consecutive 16-bit registers
- F = 33-bit float transferred using two consecutive 16-bit registers
- LE = 33-bit integer transferred using "Enron Modbus" protocol variant

The steps of programming

1: Schedule

- How many seconds are used for the schedule?
- How much data is stored?

[13] **DT80 Range DT80/81/83/85 Series 1, 3 & 3 Includes CEM30 User's Manau**

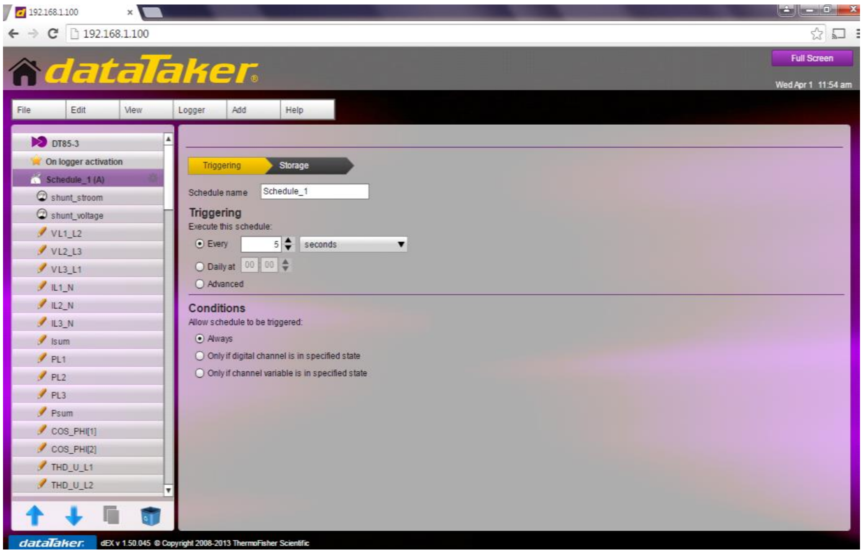


Fig. 4.14: Schedule of DT

2: Analog channels

- the voltage is determined (there are 2 analog channels: output current and voltage)
- Voltage scaling

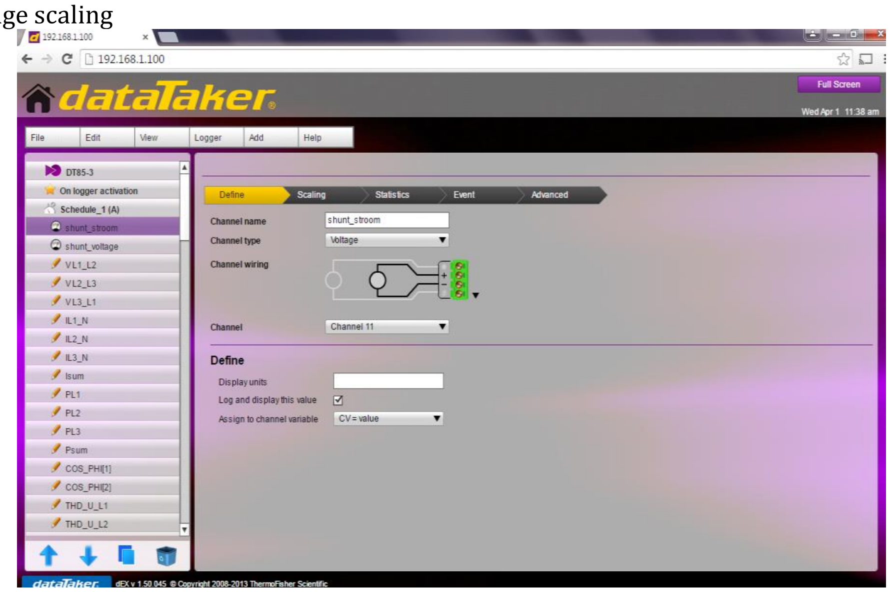


Fig. 4.15: output current of analog channel

Analog channel output voltage:

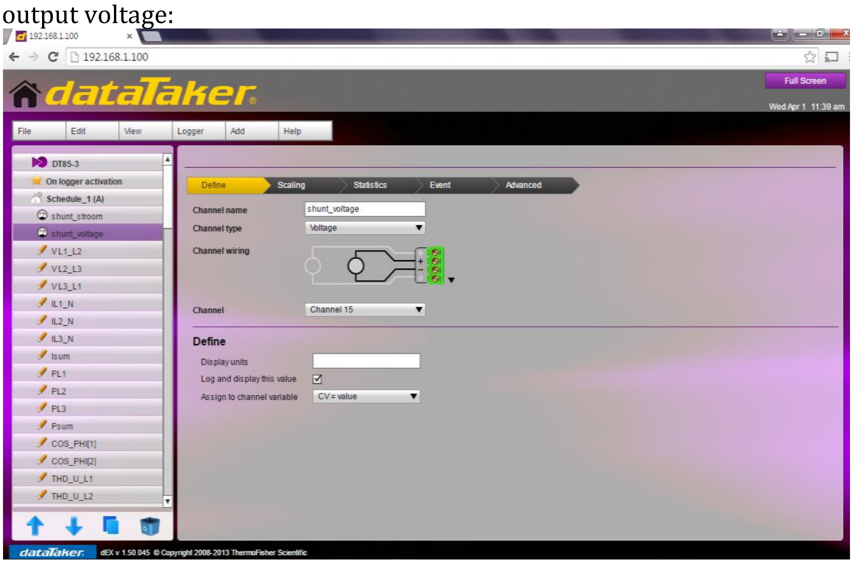


Fig. 4.16: Analog channel output voltage

3: Modbus address

1- Input voltage, use 3 phases

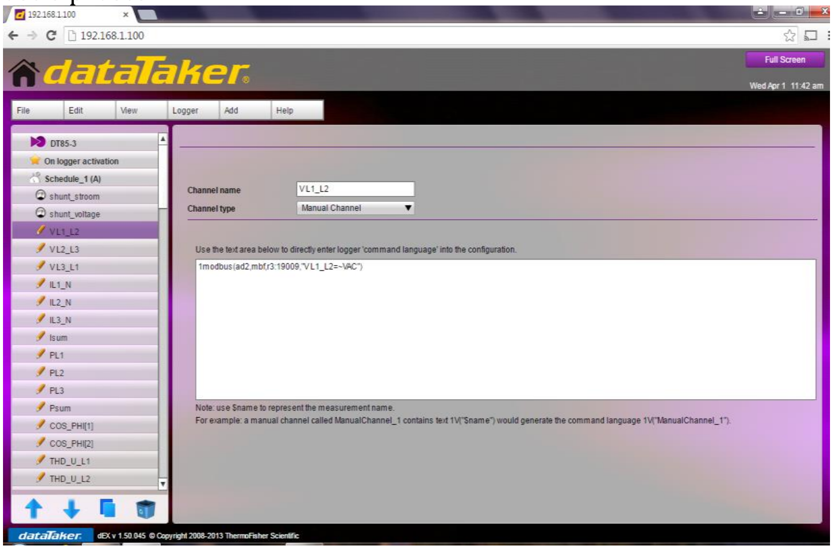


Fig. 4.17: Modbus address of phase voltage

2- Input current, use 3 phases

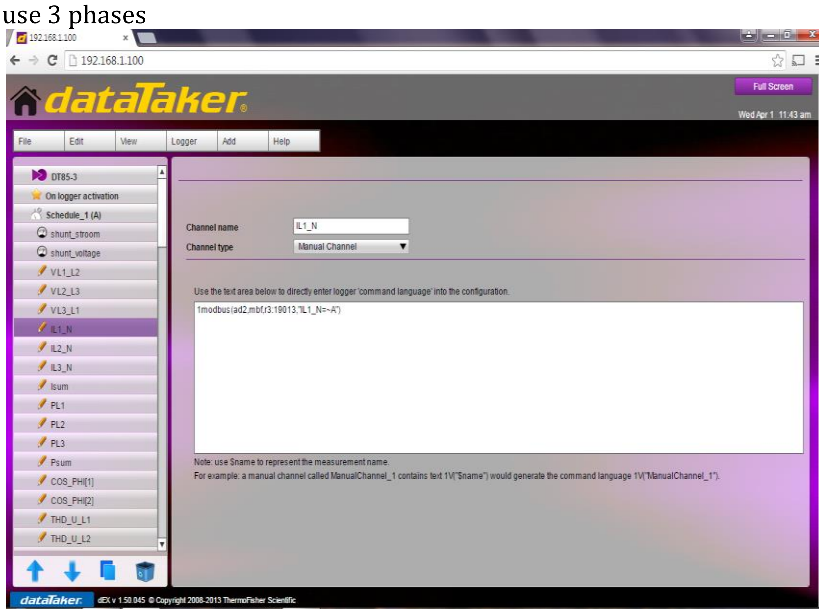


Fig. 4.18: Modbus address of phase current

3- Input power, using 3 phases and total power

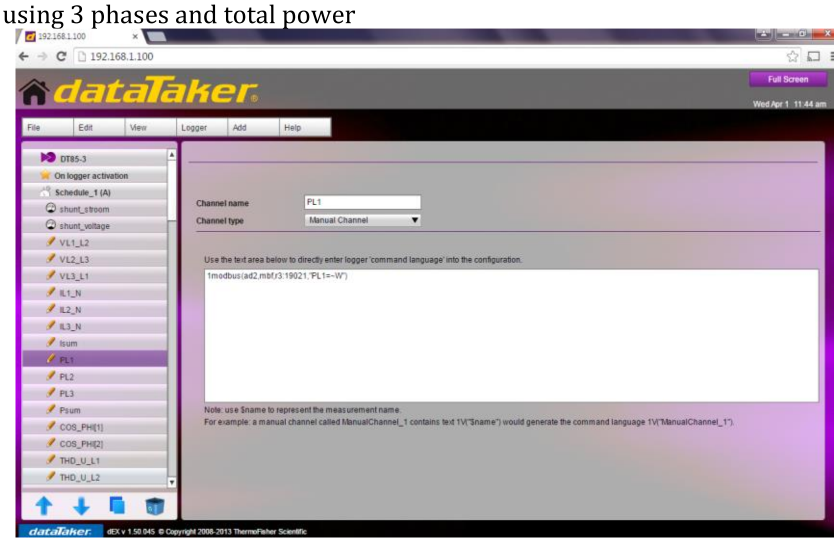


Fig. 4.19: Modbus address of phase power

Idem use Modbus address for the harmonic distortion for current and voltage, cos phi (3 phases).

4.3.3: Test setup: Variable load resistance

A variable load resistor is used in all tests. This has the option to vary in 6 steps (test 1,2). A higher resolution is achieved by several steps (27 steps in tests 2 to 6).

1: The purpose of variable load

Advance the amount of power required, which is not known to the system outputs. The amount of current depends on the following parameters: the amount of corrosion, the conductivity of the water, the speed of the water and the temperature.

Besides, the transition resistance from the anode to the cathode (the steel) can change due to the following causes:

- An anode can break or be damaged, changing the effective surface and therefore the transition resistance
- Accumulation can occur at the cathode due to scale deposits

As a result, it is not possible to say in advance at what voltage or current level the voltage sources will operate.

2: Variable load description

The description of the variable load resistance. There is a front with the following parts:

- PLC
- Control voltage
- Auxiliary relays
- Magnetic switch
- Current sensor

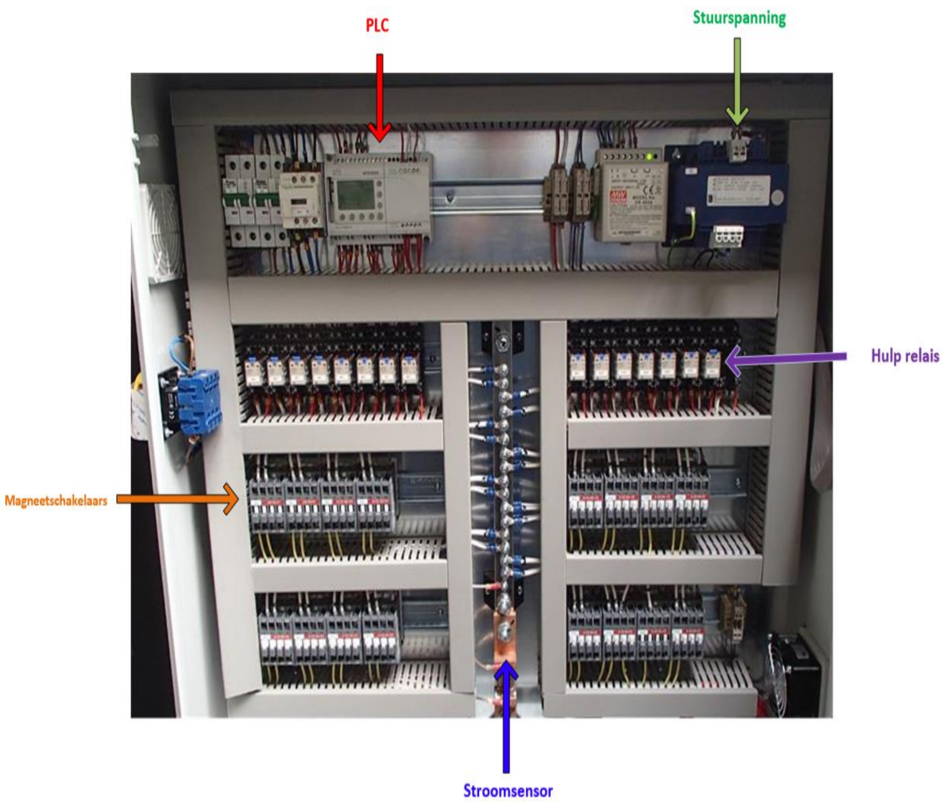


Fig. 4.20: Front side of the variable load resistor

And a back with:

- 32 lamps
- Ventilator

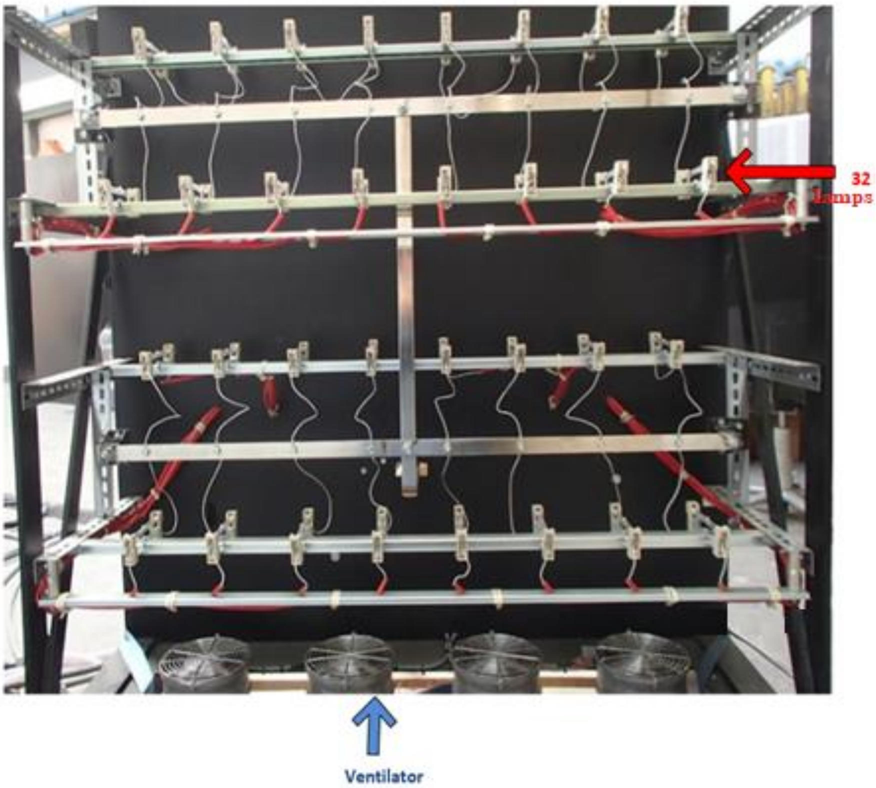


Fig. 4.21: Back of the variable load resistor

4.3.4: Programming PLC Mitsubishi Alpha 2

With Alpha 2, a simple application controller system, Mitsubishi Electric opens up a new possibility for a multi-function controller which allows one to solve a large number of control tasks by selecting one of the integrated functions.

A: Description of an application controller

A controller is a system in which multiple input signal data is recorded and internally processed, relating to different output signal data. Signals such as on and off are input through control inputs, processed in the controller by a program and forwarded to the outputs where they are turned on/off. Control is based on the principle of information processing, where all data is entered, processed and the output processing results are displayed. This requires three levels:

- An input
- A processing
- An output

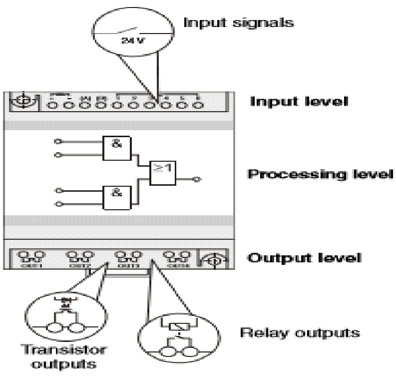


Fig. 4.22: The principle of information processing

1: An input

The input has the task of providing control signals to the processing. Parts include switches, buttons and sensors. The signals of these components are the result of the checking process and are thus delivered in the logic state of the input. The input supplies the signals in processed form to the processing.

3: Processing

The signals stored and processed by the input are processed in the processing by a stored program and logically connected. The processing has a program memory that is freely programmable. Changing the editing program is possible at any time by changing or exchanging the stored program.

3: An output

The results of the logical operation of the program, coming from the processing as output signals, can affect the state of the physical parameters.

B: Type of signals related to the controller

1: Binary Inputs

There are two types of status signals: ON and OFF or 1 and 0. The switching state is activated in the output level of the controller depending on the binary input signals. Binary signals are realized by switching contacts (push buttons, relays, switches, etc.), contactless with semiconductors (transistors) or other controllers or switching elements.

2: Analog input signals

An input signal can be represented as an analog signal with a continuously variable range. For example, analog signals may be provided by a potentiometer in the form of a variable electrical voltage. The analog value is converted to a digital value and is available for internal processing. ALPHA-controllers with a dc-voltage source offer the possibility to process analog signals 0-10 V.

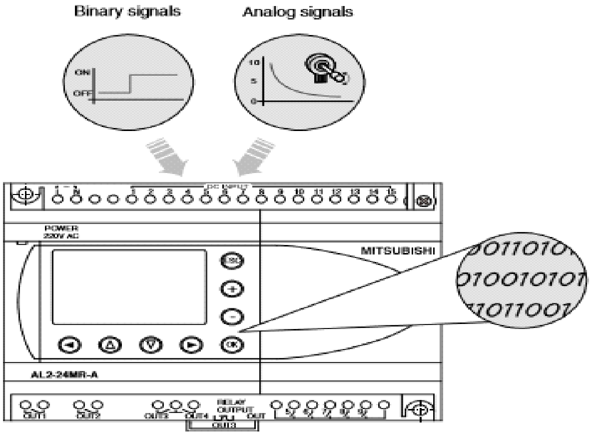


Fig. 4.23: Signals in the program:

3: programming

Programming the controller can be compared to wiring a conventional machine, but here the ALPHA controller sets the program. No complicated programming language is needed, because the pre-programmed function blocks simplify the solutions even of complicated control tasks. A function block has one or more inputs and one output. The input signals are detected, processed for to function and for the result output on the output.

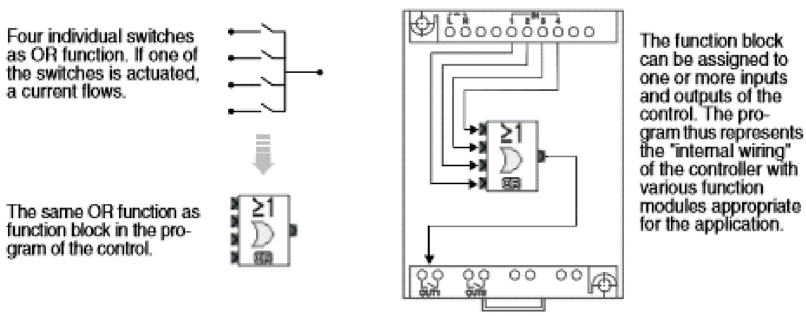


Fig. 4.24: Function block

C: Basic logic functions

The logical operations below provide an overview of the basic functions of ALPHA. In addition to the normal graph, both the AL-PCS / WIN-EU software are shown, as well as what is on the display of the Alpha controller.

1: AND operation

Series connection of points that make contact. All switches should be activated so that the power circuit is closed.

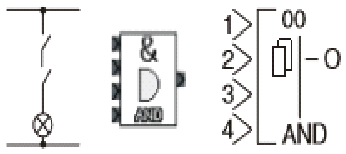


Fig. 4.25: AND operation

2: OR operation

Parallel connection of points that make contact. One switch must be activated so that the power circuit is closed.

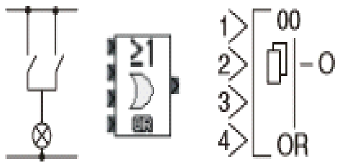


Fig. 4.26: OR operation

3: Further functions

The ALPHA controller has a large selection of function blocks that just need to be connected. as a replacement for the former relays, contactors, etc

Detecting changes in signal status

Only when the input signal is turned on, individual pulse is given at the output. The function block can also be set so that the output pulse comes when the input is opened.

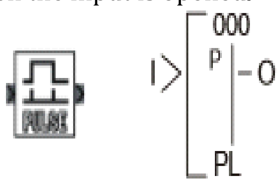


Fig. 4.27: " PL pulse-edge" function block

latch relay

The output is closed by an input pulse and opened by another input pulse.

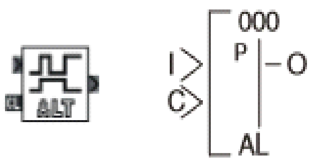


Fig.4.28: " AL " function block

Switching delay

Closing or trip delay can be selectively performed with this function block

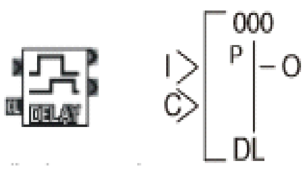


Fig. 4.29: " DL " Function block

Pulse Generator

If the input signal is activated, the output is closed for a special specific number of seconds (0 to 3267 seconds).

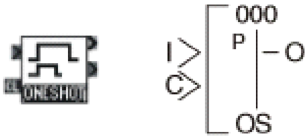


Fig. 4.30: " OS " function block

D: Programming tests

1: Programming test 1

The variable load is programmed by PLC Mitsubishi Alpha 2, i.e., a different value of load per period. The results of the first measurements are generally reasonable and as expected, but some values are not accurate enough.

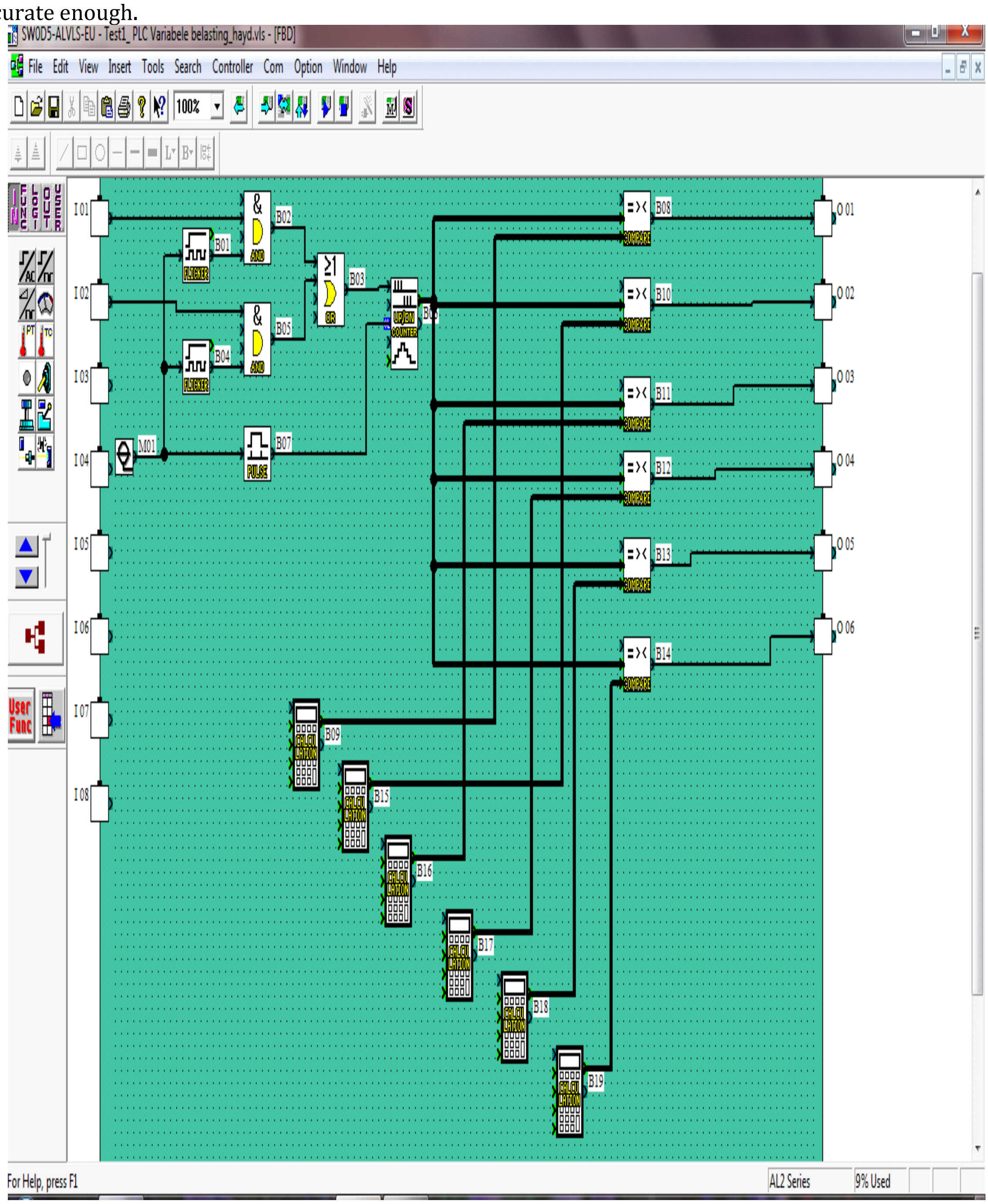


Fig. 4.31: Simulation-diagram of test 1

2: Programming test 2

Between two values of the variable load, the change of time takes results in an inaccurate measurement. After the transient, the measurement becomes accurate. So, use a manual load change, but that is not convenient. Or program the variable loads by PLC and stop the measurement during any transient time.

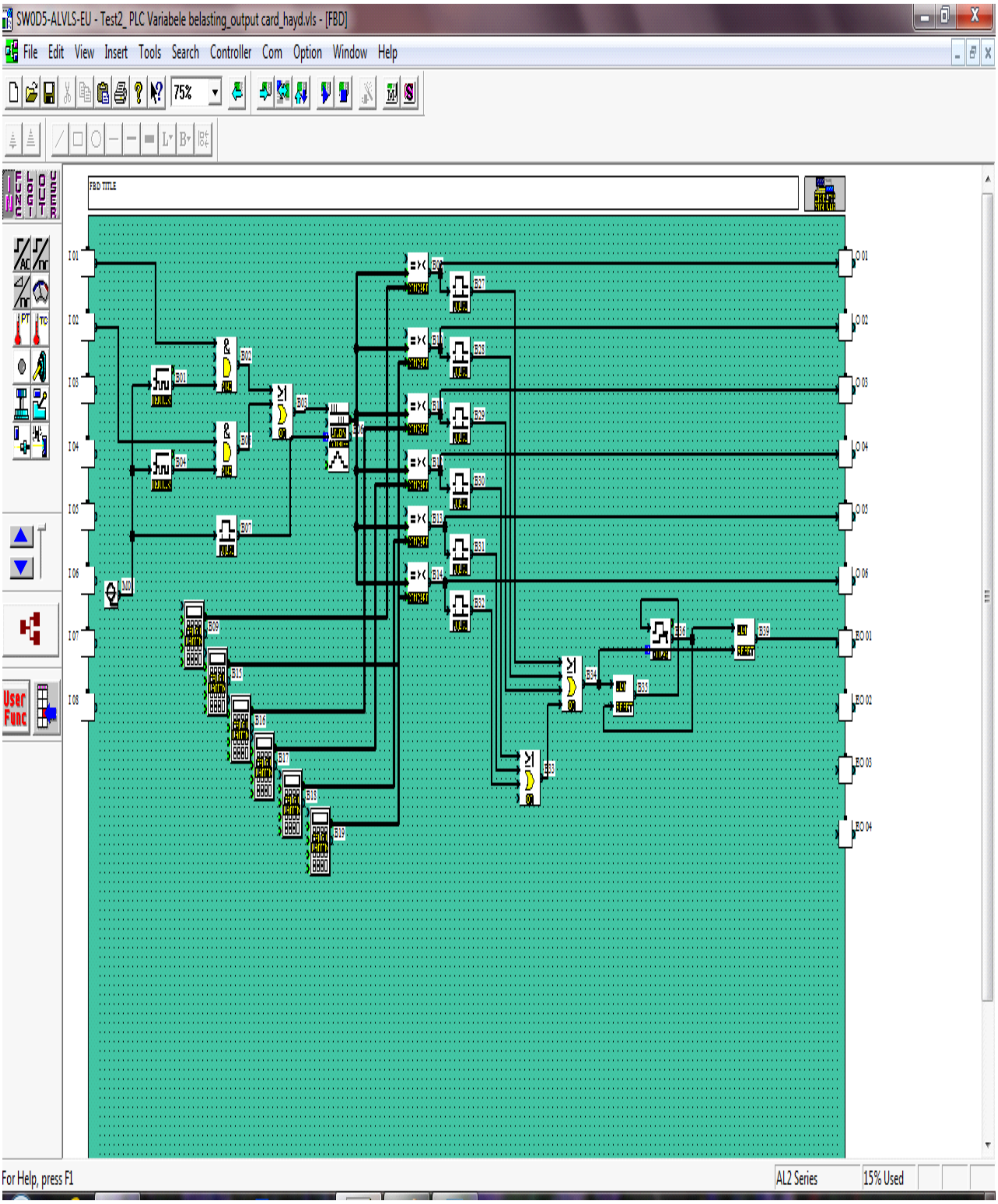


Fig. 4.32: Simulation-diagram of test 3

3: Programming test (3 t/m 6)

In test 3, all steps are automatically performed: this saves time and effort. See the diagram:

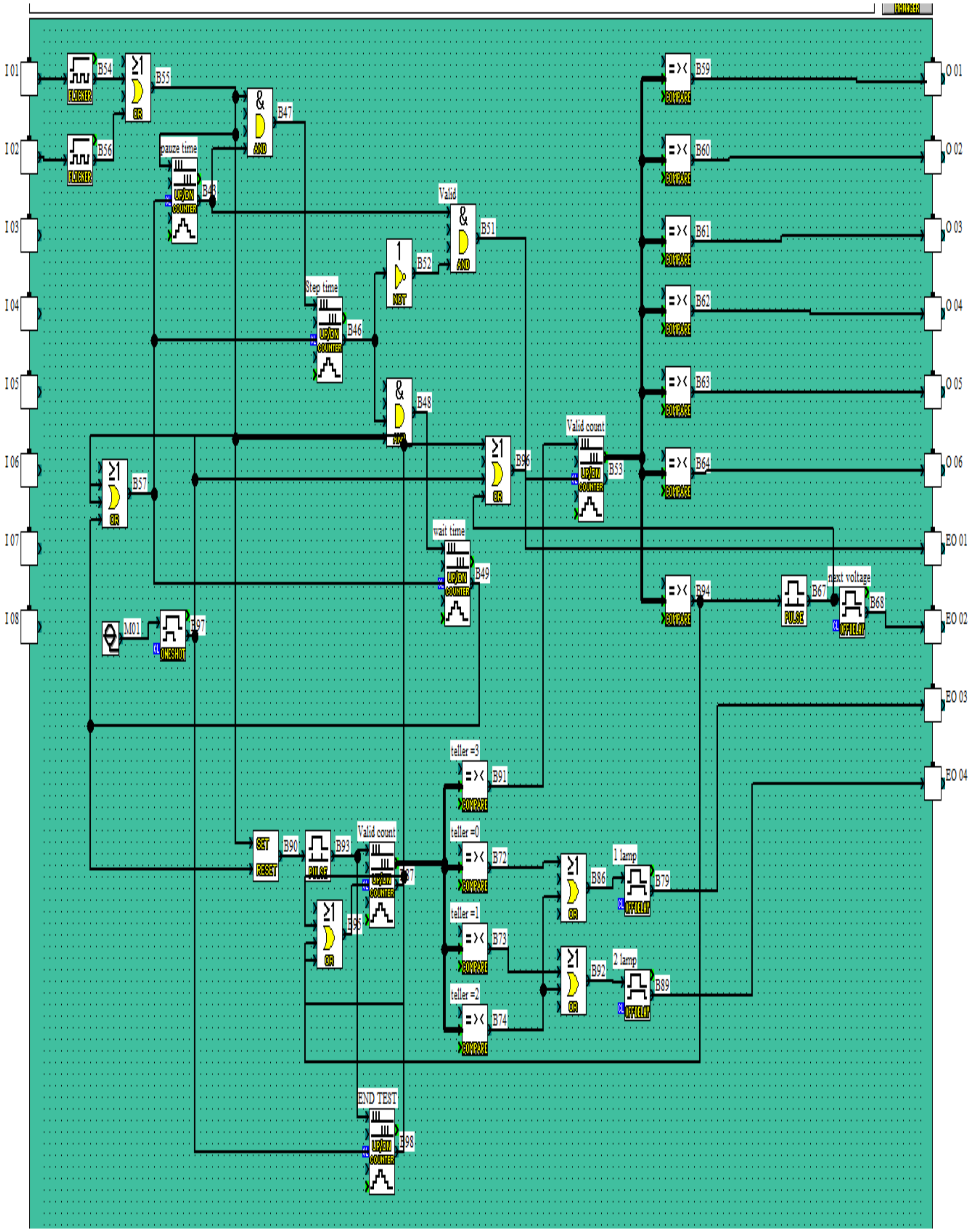


Fig. 4.33: Simulation-diagram of test 3

4.3.5: Calculation of resistance per lamp

As for the lamp in the cabinet, the relationship between Vout and Rb is not linear. The resistance of each lamp should be calculated. The graph below shows the relationship between Vout and Rb for the 6 steps according to the measurement result of test 2.

To create the variable load, a base of 32 lamps of 300 W each one is used. There are 4 rows of 8 lamps: the total power is 9600 W @ 24VDC (in full load). There are six steps for the variable load. Three for the left side of the box and 3 for the right side (for tests 1 and 2). They control a number of switches that turn all lights ON or OFF. The following table shows each step with the number of lamps:

Step	Lamps
1	4
2	10
3	16
4	20
5	26
6	32

Table 4.2: Each step with the number of lamps

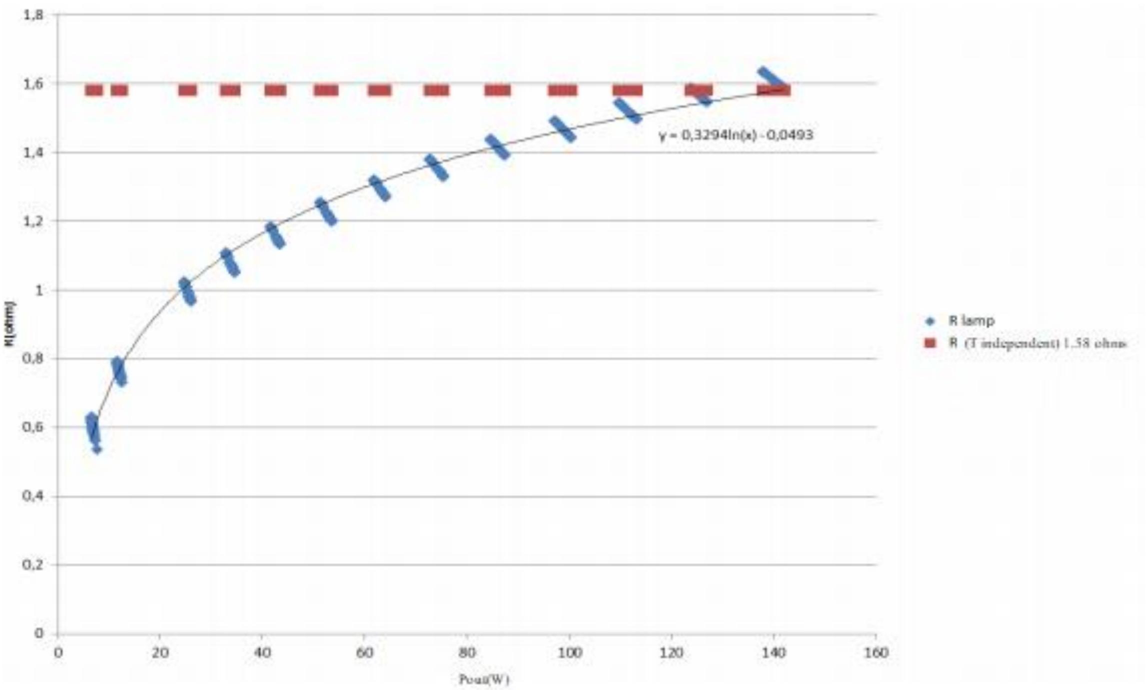


Fig. 4.34: Pout VS R-lamp

The trend line of this graph gives the formula of the resistance per lamp and the output power:

$$R(Pout) = 0{,}3394 \ln (Pout) - 0{,}0493 \quad ... (4.1)$$

The power of the lamp:

$$Rl = \frac{Vout^2}{P\ out} \quad ... (4.2)$$

The values of Puit and R1 are known. This means that the value of the U from is also known. The relationship between R1 and U out is drawn in a graph. The resistance of the lamp changes depending on the output voltage.

$$Rl = 0{,}3394 \ln (V\ out) + 0{,}7837 \quad ... (4.3)$$

The resistance of the lamp vs the output voltage: it says in the Datasheet that one must start with 10% of the nominal voltage. That is why we start with 3 V.

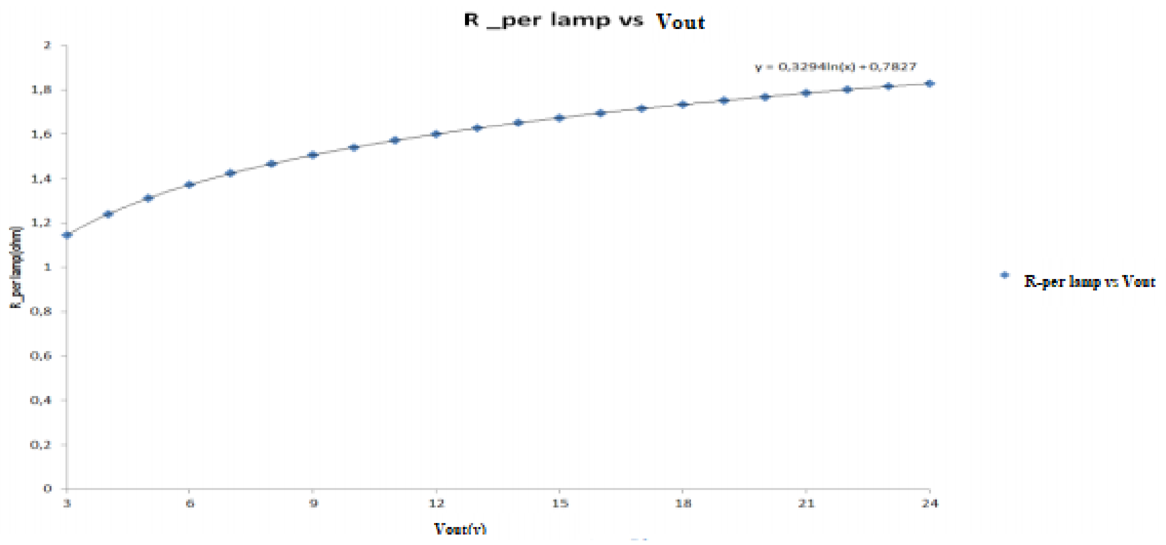


Fig. 4.35: Vout va Rl

See the following table:

V(v)	R_per one lamp
3,0	1,1446
4,0	12393
5,0	1,3128
6,0	1,3729
7,0	1,4237
8,0	1,4677
9,0	1,5065
10,0	1,5412
11,0	1,5726
13,0	1,6012
13,0	1,6276
14,0	1,6520
15,0	1,6747
16,0	1,6960
17,0	1,7160
18,0	1,7348
19,0	1,7526
20,0	1,7695
21,0	1,7856
22,0	1,8009
23,0	1,8155
24,0	1,8296

Table 4.3: The values of R(Vout)

According to the table above, the values of the resistance of the lamps are not accurate, because both cable resistances (back and forth) are involved.
According to the rules of the voltage divider, the voltage through variable load is:

$$\boldsymbol{V2} = \frac{\boldsymbol{V1\ Rb}}{(\boldsymbol{Rh} + \boldsymbol{Rt}) + \boldsymbol{Rb}} \ \dots (\mathbf{4.4})$$

in which:
Rb = variable load resistance
Rh = resistance cable
Rt = resistance cable back

See the following figure:

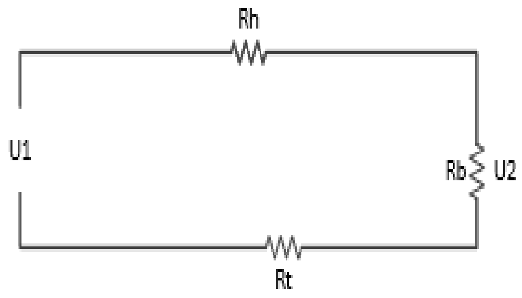


Fig. 4.36: The voltage divider of R cable and R load

Obviously, as Rb increases, the voltage drops through the cable decreases and vice versa. The goal is to determine the resistance per lamp and therefore measurements are taken as close to the resistance as possible. The figure below shows the graph of Vout vs Diamond:

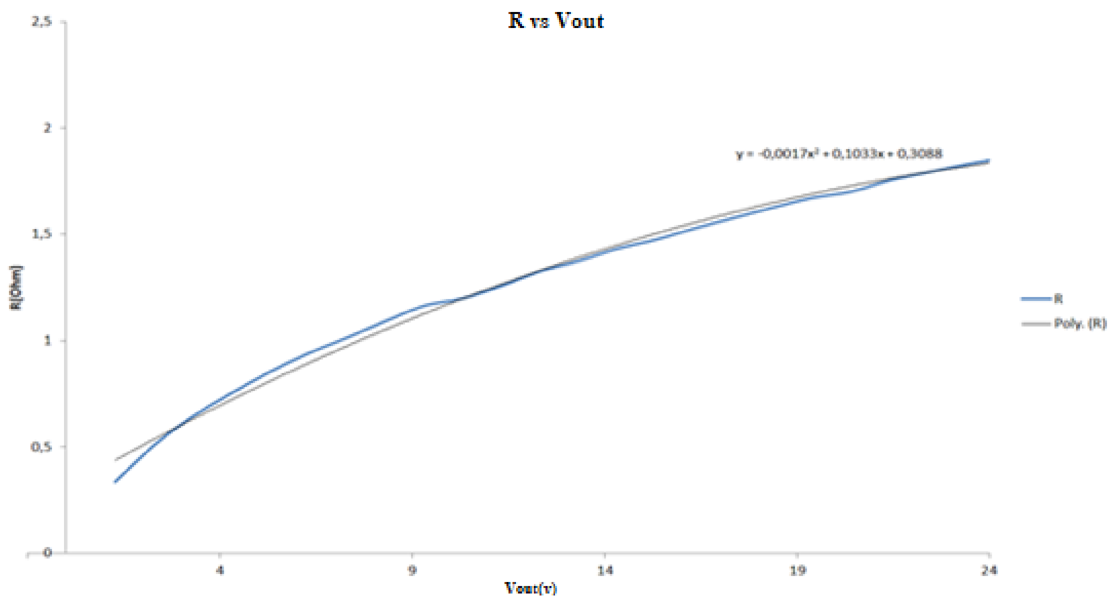


Fig. 4.37: Vout vs R

The resistance of the lamp changes depending on the output voltage. By following the trend line of this graph, the next formula is obtained:

$$Rl=-0.0017\,Vout^2+0.1033\,Vout+0.3088 \quad ... (4.5)$$

4.3.6: Optimization variable load

1: Graphs

Three are used for test 1 and 3 TDK-HWS-HWS's of 15V - 1500V (300 A). The relationship between V_{out} and I_{out} is shown in the following graph:

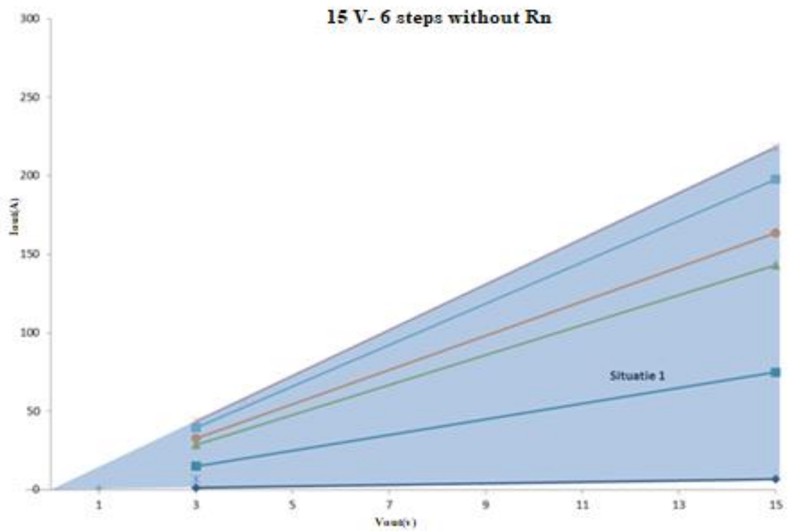


Fig. 4.38: Vout vs Iout for 6 steps (15 V)

Each point in the graph represents a load resistance. In the relationship between Vout and Iout, the properties of the TDK-HWS-HWSs are only seen in the lower part, but in the high part (high output current) the properties do not exist and so this part calls for a new resistor to recover all properties.

2: New resistance

In test 3 the properties of the output voltage and the output current are not representative enough, because not all parts are filled in because Rb is not small enough. So, a new resistance must be sought for new data. See the following figure:

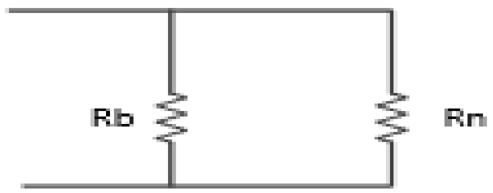


Fig. 4.39: Variable load with a new resistor

3: Calculate Rn en Rtot

The maximum output power is not reached. The new load is applied in parallel; the TDK-HWS must deliver more power. Now the maximum Rb with 32 lamps is known.
For three parallel TDK-HWS's are nutrition:
Maximum P_{out} is 3x 1500W = 4500 W
Maximum resistance for 32 lamp is R_b = 0.049 Ω
Maximum V_{out} =15 V
Maximum I_{out} (3 x Ps) = 300 A
R_{tot}= Total tax
R_b = the tax (4 lamps, 10 lamps, etc.)
R_n= The new load is arranged in parallel

4: Rn for TDK-HWS– 15 V

- ***Situation 1(without Rn)***

Adjust the formulas:
Put in the place of Vout 15 V and one gets $R_{l\_15\ v}$ =1.48 Ω,
R t1_max= 1,48 Ω (1 per lamp)
R t1_ min=0,046 Ω (32 lamps)

- ***Situation 2(with Rns3)***

R t3_max= 0,046 Ω
R b_ max= 1,48 Ω, R b_ min= 0,046 Ω

$$\frac{1}{R_{ns2}} = \frac{1}{R_{t2-max}} - \frac{1}{R_{b-max}} \quad \ldots (4.6)$$

$R_{ns2} = 0.047$ Ω

$$R_{t2-min} = \frac{R_{b-max}\, R_{ns2}}{R_{b-max} + R_{ns2}} \quad \ldots (4.7)$$

$R_{t2-min} = 0.023$ Ω

- ***Situation 3 (with Rns3)***

R_{t3-min} = 0.033 Ω
R b_ max= 1,48 Ω, R b_ min= 0,046 Ω
R_{ns3} And $R_{t3-min}$are given by formula 4.6 and 4.7:
R_{ns3}= 0.0334 Ω and R_{t3-min} = 0.0155 Ω

- ***Situation 4 (with Rns4)***

R_{t4-min} = 0.0155 Ω
R b_ max= 1,48 Ω, R b_ min= 0,046 Ω
R_{ns4} And $R_{t4-min}$are given by:
R_{ns3}= 0.0157 Ω and R_{t3-min} = 0.0117 Ω

5: Rn for TDK-HWS– 24 V

Ones similarly obtained the added values of resistors R.
Put in place of Vout 24 V and ones gets $R_{l\_34\ v}$ = 1.81 Ω (the formula L.5).

See the following table:

Situate	Load	15 V	34 V	Rn_15 V(Ω)	Rn_34 V(Ω)
1	Min.	0,046 Ω	0,057 0Ω	∞	∞
1	Max.	1,480 Ω	1,810 Ω		
2	Min.	0,023 Ω	0,0280 Ω	0,047 Ω	0,055 Ω
2	Max.	0,046 Ω	0,057 Ω		
3	Min.	0,0155 Ω	0,0190 Ω	0,0334 Ω	0,0384 Ω
3	Max.	0,023 Ω	0,0280 Ω		
4	Min.	0,0117 Ω	0,0144 Ω	0,0117 Ω	0,0193 Ω
4	Max.	0,0155 Ω	0,0190 Ω		

Table 4.4: The values of maximum, minimum and the new resistances (15 V and 34 V)

- ***Connection Rn***

There are three different values for En that should be connected to the load connected in parallel. The value of the tax in the situation 2 is R_{ns3}= 0.047 Ω. In practice it is used 6 x 0.022 Ω in series connection in parallel with 6 x 0.022 Ω in series (0.066 Ω). See the following figure:

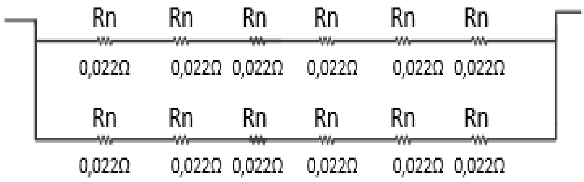


Fig. 4.40: The new resistance in the practice

The value of the load in situation 3 is R_{ns3}= 0.0234 Ω. In de practice is used 6 x 0.022 Ω (in series) connected in parallel four times with each other. In situation 4 that process repeats itself with another addition of 6x 0.022 Ω extra (connected eight times in parallel with each other).
The added resistors have almost the same values, so these resistors in both cases (TDK-HWS– 15 V and TDK-HWS– 24 V) can be used.

6: Variable load extension

- ***Description***

Now 27 steps are used. See the following table for the number of steps and lamps.

Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Lamps	1	2	3	4	5	6	7	8	9	10	11	16	17	18	19	20	21	22	23	24	25	26	27	29	30	31	32

Table 4.5: The number of steps and lamps

There are 27 steps designed for reliable resolution. See the following graphic for TDK-HWS15 V-1500 W.

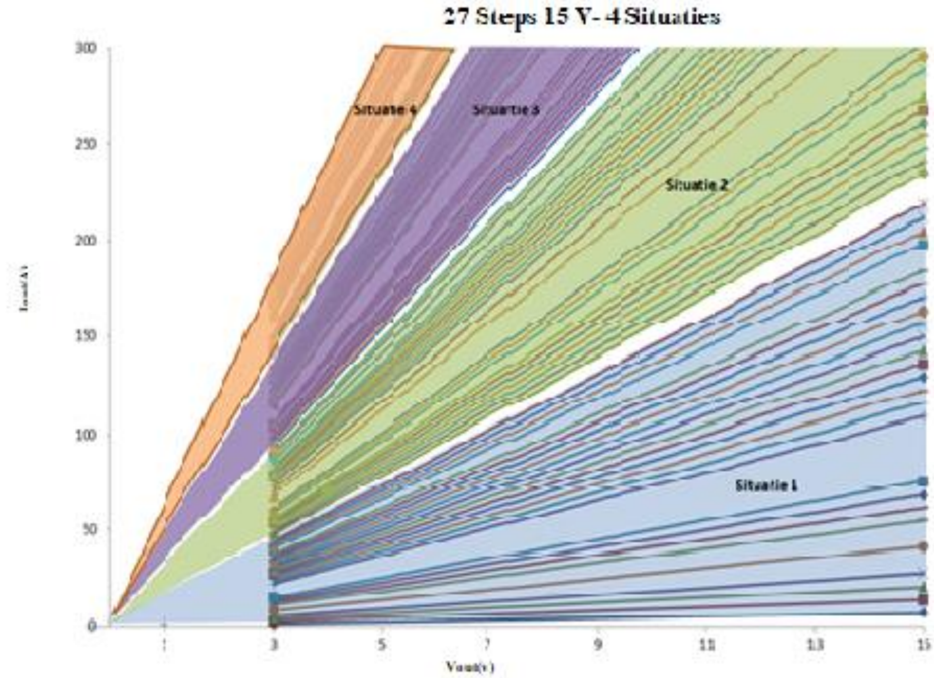


Fig. 4.41: Vout vs Iout for 37 steps and 4 situations (15 V)

Situations 1 and 2 fill the largest area of the graph, while situations 3 and 4 hardly do. To save time and take fewer steps, 3 and 4 are omitted. See the following graph for TDK-HWS15 V-1500W in situation 1 and 2.
Same principle in TDK-HWS 24 V - 1500W in 4 situations. See the following.

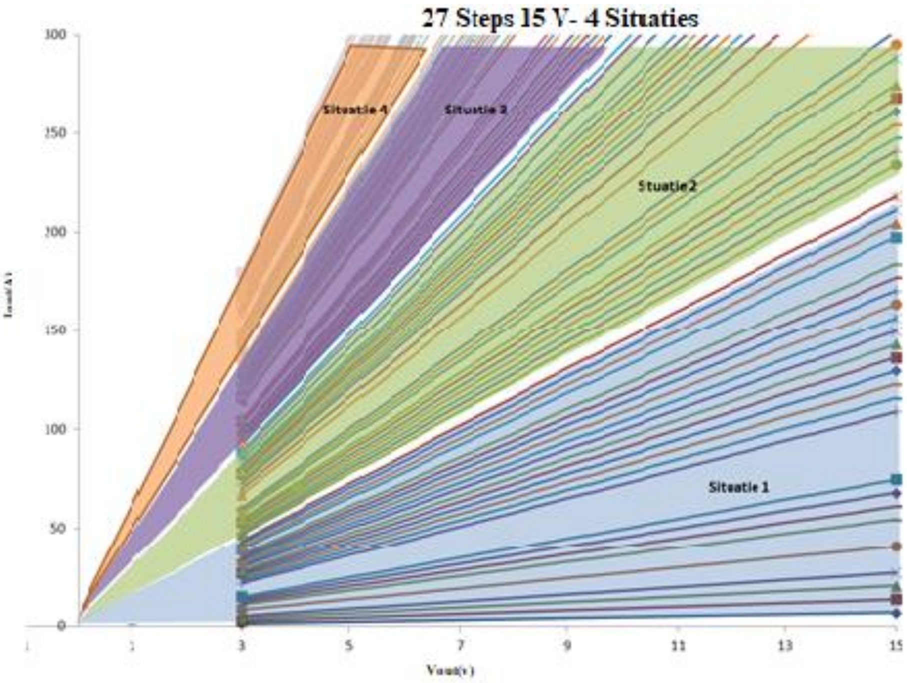


Fig. 4.42: Vout vs Iout for27 steps and 4 situations (24 V)

7: Sub-conclusion

It is recommended to perform two tests for the optimization of the variable load resistance. In the first test a variable load is used and in the second test a new resistor is added.

4.3.7: Test setup

1: Block diagram

All components are collected in one cabinet, which is the prototype for the ICCP system. First of all, a description is given of the cabinet and its dimensions in mm.

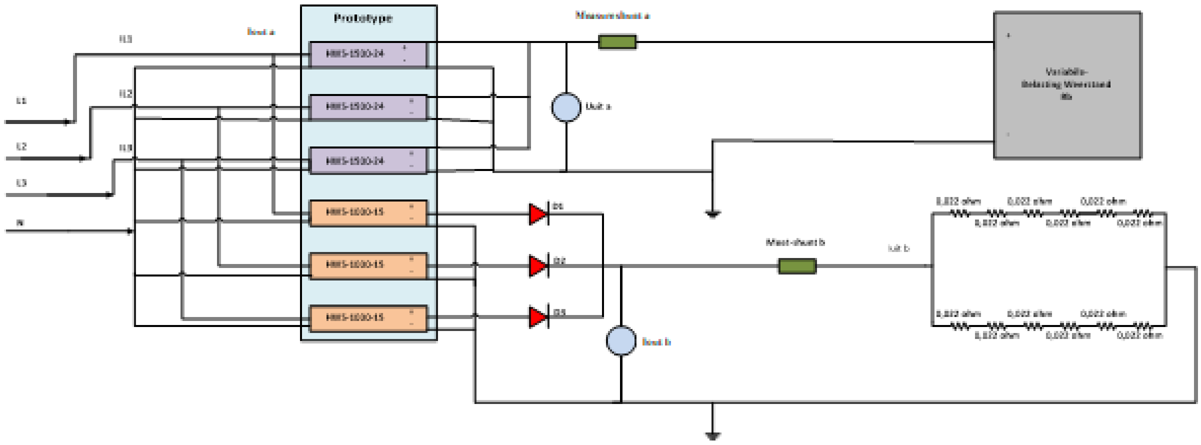


Fig.4.43: Scheme of prototype ICCP

3: Resistance load during test

For the optimization of the variable load resistance, it was recommended to perform two tests. This advice has already been applied in tests 3, 4 and 5. In the first test a variable load is used and in the second test a new resistor is added.

The variable load of 4500 W (32 lamps of 300 W each, with a total maximum power of 9600 W) is used for 3x TDK-HWS-HWS's 1500-34 (4500 W). The 6 plates (6x 0.022 Ohm) are connected in parallel with each other for one TDK-HWS1000-15 (1000 W).
This fixed tax also applies to the other two TDK-HWS-HWS 1000-15. A solution is the use of three diodes (VD = 0.7 V) which make it possible to use one load with 3 TDK-HWS-HWS's. See the following Fig, 4.44:

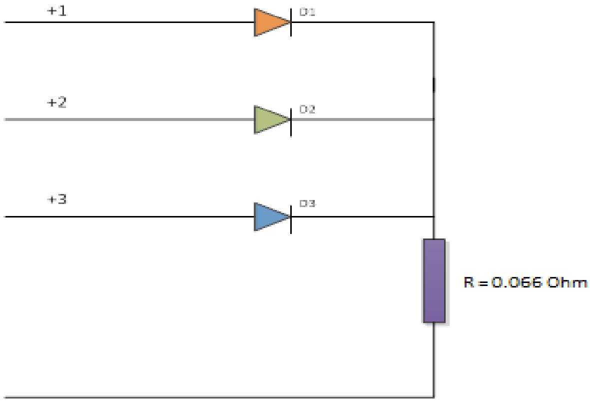


Fig. 4.44: Load resistance

The total power of the fixed load is:

$$\mathbf{R} = \frac{\mathbf{V^2}}{\mathbf{P}} = \frac{(\mathbf{15 - 0.7})^2}{\mathbf{3\,.\,1000}} = \mathbf{0.068}\,\Omega \;\;\ldots.(\mathbf{4.8})$$

3: Sub-conclusion

- One fixed resistance load is used in place of the three loads of HWS 1000-15.
- The variable resistor is used as the load of HWS 1500-24.

5: Measurement results of ICCP

5.1: Introduction

The measurement results should be analysed and then the graphs optimized. There are three types of tests which are the current harmonic (test1, test2 and test3) of prototype ICCP.

As concerns the current harmonic: the results obtained by measurements of THD-V and THD-I (1 – 40) Harmonics of the 1st phase of voltage and current and determined by formulas are then compared with each other. It has to be established whether HWS falls within the Harmonic standard ICE61000-3-2.

It defines how the regulator works to limit the input current and how the maximum values of the current, voltage and power are set. Then the parameter of the controller is calculated and the parameters are determined from the partial measurements. Eventually, it follows the test of the prototype ICCP.

5.2: Measurement results: Analyse and Optimize

In the tests, measurements are made of, among other efficiencies, the power factor, the current and voltage harmonic, the output current and output voltage. Based on the results of these tests, the measurement setup is assessed and the measurement results are verified. The purpose of the measurements is to determine the current harmonic and current limit.

5.2.1: Test 1

In the first three tests, device under test of HWS 1500-15 is used. (The 1000-15 and 1500-24 were not available). The test is analysed. The graphs are optimized. Finally, the conclusions and recommendations are discussed. See Appendix F – Results and graphs of Test 1.

- ***Recommendations***

The software is programmed according to 1 measurement with 1 result per second via the FieldLogger. The variable load is programmed by PLC Mitsubishi Alpha 2, i.e., a different value of load per period. The results of the first measurements are generally reasonable and as expected, but some values are not accurate enough. There are several reasons:

Recommendation1:

The time it takes for the change to take an inaccurate measurement results in an inaccurate measurement between two values of the variable load. After the transient, the measurement will be accurate. So, use a manual load change, but that's not helpful. Or program the variable loads by PLC and stop the measurement during each transient time. See fig.5.1.

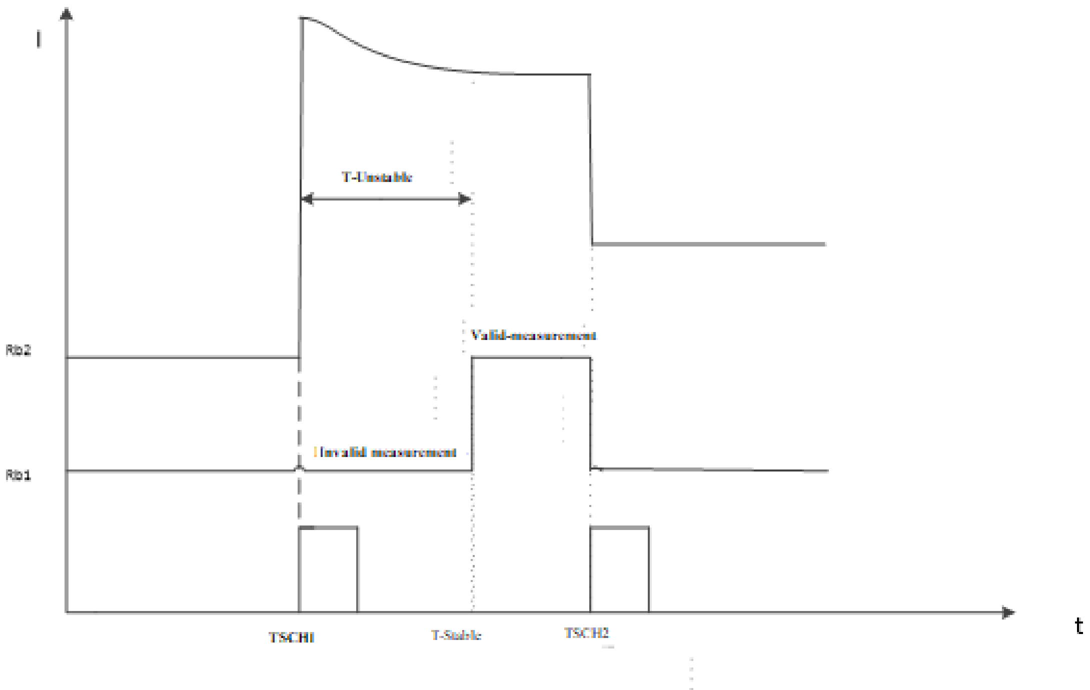


Fig. 5.1: The variable load measurement

Recommendation 2:

Zero-point current calibration.

Recommendation 3:

During control measurement, both sides of the current should be measured.

Recommendation 4:

During the measurement, the value of the output voltage is not accurate, namely the voltage between the positive terminal and the negative terminal does not appear to be equal to the load voltage. So, measure as close to the TDK-HWS as possible, because the long cable between TDK-HWS and the variable load gives more voltage drop.

Recommendation 5:

Adjust the measurement.

Recommendation 6:

Other uses data logger (more channels).

Recommendation 7:

Voltage drops the graphs P_{out} vs Cos phi, V_{out} vs Cos phi, I_{out} vs I_f, Vout vs I_f.

Recommendation 8:

power Lines in I_f vs P_{out} are added.

Recommendation 9:

Add the chart of returns efficiency (η vs P_{out}).

Recommendation 10:

There are three main graphs for the calculation of the input power limit: I_f vs P_{out}, Cos phi vs P_{out}, η vs $P_{out.}$

Sub-conclusions

Several conclusions can be drawn:

- The measurement can be improved: program the variable loads by PLC and stop the measurement during each transient time.
- The voltage should not be measured at the points of the variable load RB, but at the points Vout of DC-TDK-HWS supply.

5.2.2: Test 2

In test 2, the same measurements were made as in test 1, but these steps are improved by a new insight obtained by test 1, see Appendix G - Results and graphs of test 2.

- ***Recommendations***

Recommendation 1:

In previous tests (test 1 and 2) the way of working was such that the output voltages were manually changed. This turns out to be a time-consuming activity. It is now recommended to run the activities automatically. This can be done by optimizing the load resistance.

Recommendation 2:

Maximum power is not achieved. The solution of this problem is: it should be requested in optimizing the load resistance.

Recommendation 3:

Current graphs should be optimized to produce the valuation easier and clearer.

Sub-conclusions

Several conclusions can be drawn:

- Measurements no longer contain noise and give correct values. This means that the measured values can be used for assessment. The Test Setup is therefore suitable.

- The relationships found in the graphs are approximately linear, but not complete. For this, the graphs have been optimized, so that the linearity becomes visible and the graph can therefore be assessed.

- The variable load resistance now does not have the most optimal value, which means that test is not carried out at all relevant resistance values. Also, the maximum output power is not reached. This requires an adjustment to the variable resistor.

The graphs are optimized, see Appendix H – Optimization rating graphics.

5.2.3: Test 3

In test 3 the same steps are taken as in tests 1 and 2, but these steps are improved by a new insight obtained by tests 1 and 2. To save time it is better to perform the tests automatically to feed, see Appendix I- Results and graphs of test 3.

In test 4 the HWS 1500-24 is used, see Appendix K-Results and graphs of test 4. In test 5 the HWS 1000-15 is used see Appendix K-Results and graphs of test 5. The prototype ICCP test is performed, the prototype ICCP.

Test nr.	HWS	Measure-logger	Load resistance (Steps)	Measuring method
1	1500-15	Field Logger	6	Not automatic
2	1500-15	Data Logger	6	Not automatic
3	1500-15	Data Logger	27	Automatic
4	1500-15	Data Logger	27+ Rn	Automatic
5	1000-24	Data Logger	27+ Rn	Automatic
6	Prototype	Data Logger	27	Automatic

Table 5.1: The tests

5.3: Measurement results: Current harmonic

5.3.1: Determining of THD V and THD I

A common deviation from a pure sinusoidal voltage and current waveform is harmonics. In this case, the waveform contains not only a component at the fundamental frequency (50 Hz), but also some components at frequencies that are a multiple of that (100 Hz, 150 Hz, etc.). Under the influence of these harmonics, the waveform is distorted and peaks can occur that are much larger than with a sine wave.

Total harmonic distortion of a signal is the measure of the harmonic distortion present and is defined as the ratio of the sum of the powers of all harmonic components or harmonics to the fundamental frequency or fundamental power.

Non-linear loads include rectifiers, switched-mode power supplies (computers), frequency regulators, LED lighting, energy-saving lamps, dimmers, induction ovens, etc. Non-linear systems include almost all devices in which semiconductors are incorporated, such as solid-state relays, transistors, diodes.[14]

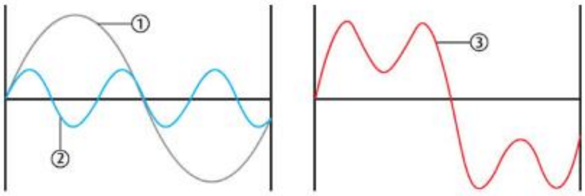


Fig. 5.2: Harmonic distortion

- ***Determining of THD V***

Other definitions are also in use. Several authors define THD as an amplitude ratio rather than a power ratio. This results in a definition of THD which is the square root of this form of stress. In the case of voltages, the definition becomes the following:

$$\boldsymbol{THD\ V} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1} \quad \dots (5.1)$$

According to the prototype results, the THD V are calculated and measured: see table 5.3:

IL1_N= (A)	THD_V_L1_measu-rement (%)	THD_V_L1_calculate (%)
9,179795323	2,746937431	3,743321885
8,397905789	2,713507103	3,708144152
7,348039752	2,616969573	3,610781499
6,388027336	2,54381901	3,536119691
5,598646442	2,437163338	3,430735726
4,57309925	2,309583848	3,304297853
3,821572372	2,22 8738677	3,22 5936485

Table 5.2: THD V calculating and measurements

- ***Determining of THD I***

THD of current or voltage is equal to the effective value of the harmonics divided by the effective value of the fundamental. In the case of distorted current, the equation is:

[14] http://www.euro-index.nl/nl/klantenservice/euroinfo/netvervuiling-harmonischen/

$$THD\ I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_n^2}}{I_1} \quad \ldots.(5.2)$$

For the results of THD I calculations and measurements: see table 5.3:

IL1_N= (A)	THD_I_L1_measurement (%)	THD_I_L1_caculate (%)
9,179795323	17,30978846	17,2 5514456
8,33473531	18,82968404	18,77686451
7,304067053	20,18436919	20,15930864
6,385543071	21,38054759	21,34693137
5,597368957	21,51339137	21,49711521
4,578393645	21,03959429	31,00775932
3,5738368	24,002343	24,128534

Table 5.3: THD_I calculations and measurements

5.3.2: Compare results with requirements

In the standard IEC 6100-3-2 for devices, requirements are set for the harmonic currents that may be present in the current drawn from a device. The maximum harmonic currents in a device are up to and including a nominal current of 16 A. The maximum harmonic current for the third harmonic is 2.30 A. Depending on what was measured for the prototype test, the maximum harmonic current for the third harmonic is 1.44 A. For the current harmonics of 2-7, see the following figure:

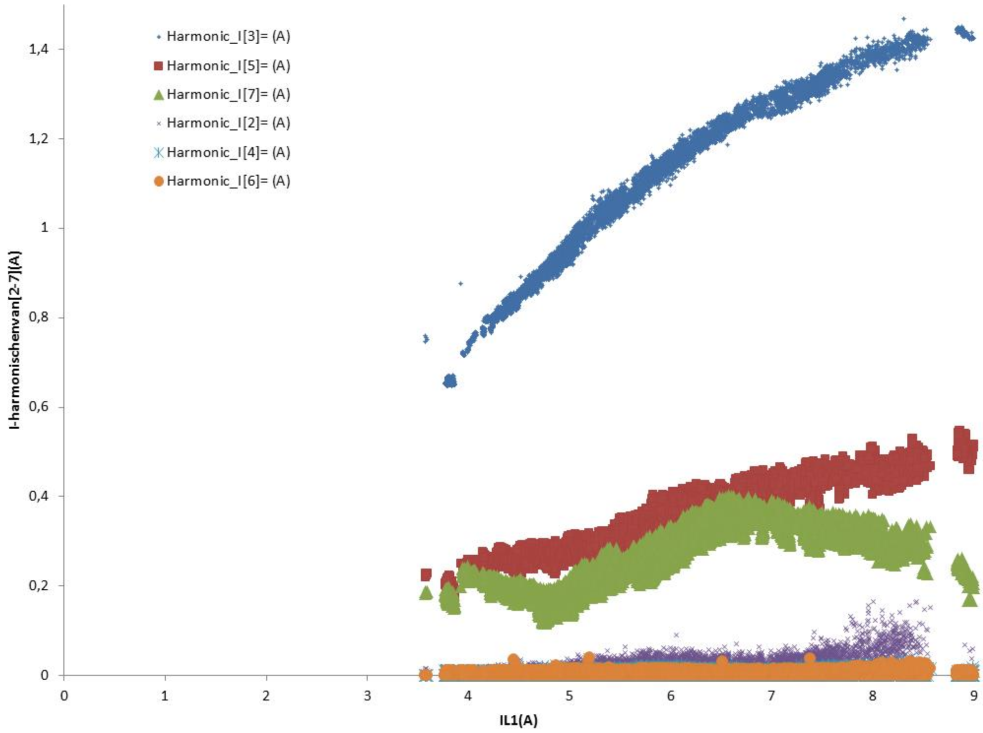


Fig. 5.3: Current harmonics of 3-7

The results of the harmonics and the data of standard ICE61000-3-2 are compared and determined. The results are within the norm. For more information, see Appendix J-Results and graphs of current harmonic.

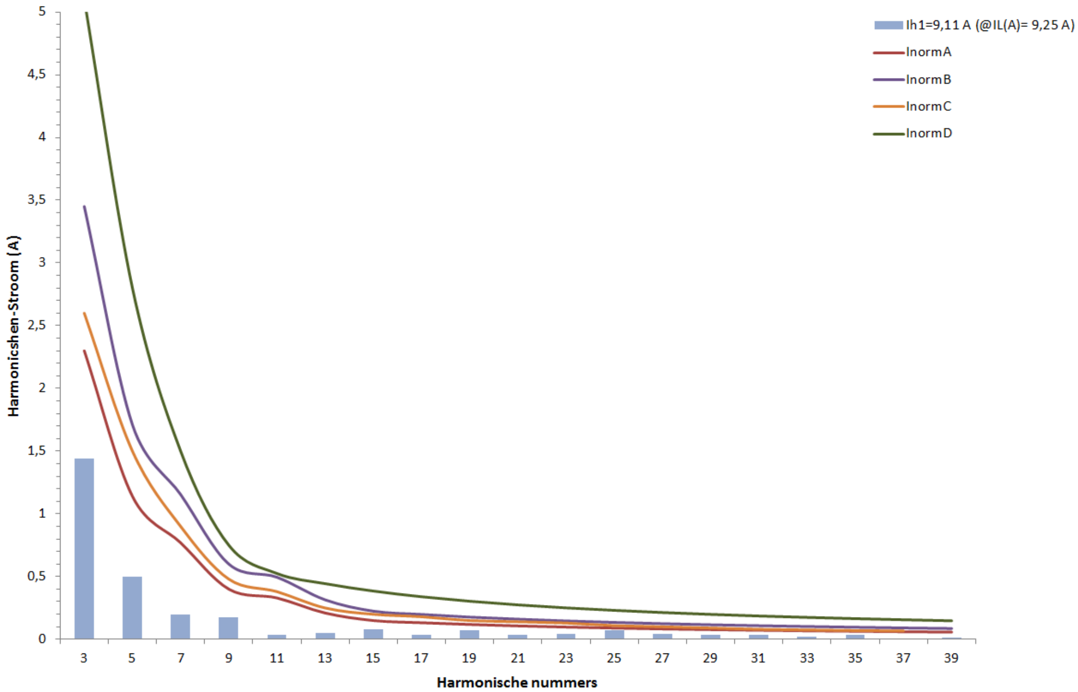


Fig. 5.4: Current harmonic of 3-39

5.3.3: Sub-conclusion

The current harmonics of HWS is within the standard of IEC 61000-3-2.

5.4: Measurement results: Current limit

5.4.1: Block diagram

The measurement and control cabinet has 3 parallel TDK-HWS-HWS's of 1500-24 whose input current should be limited. The same principle applies to 3 separate TDK-HWS-HWS's of 1000-15. See fig. 5.5.

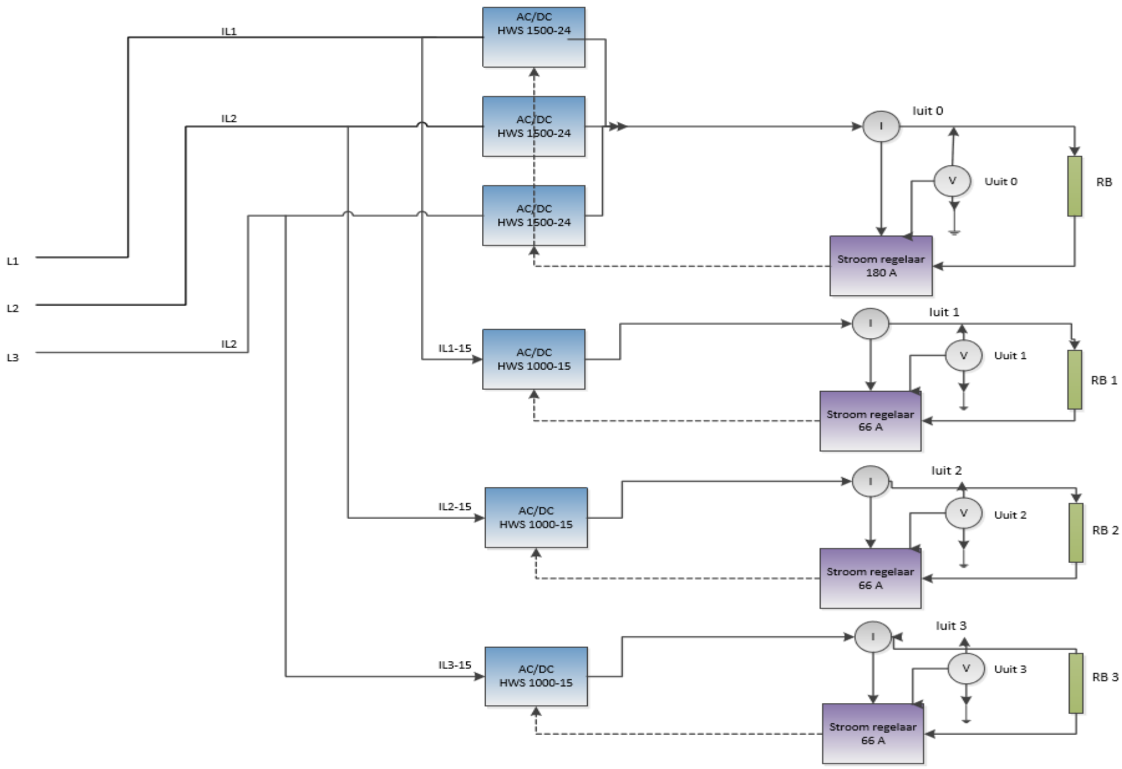


Fig. 5.5: ICCP controller block diagram

5.4.2: Derivation of output power and input current

The relationship between the input current and the output power, for three parallel TDK-HWS's from 1500-24, is:

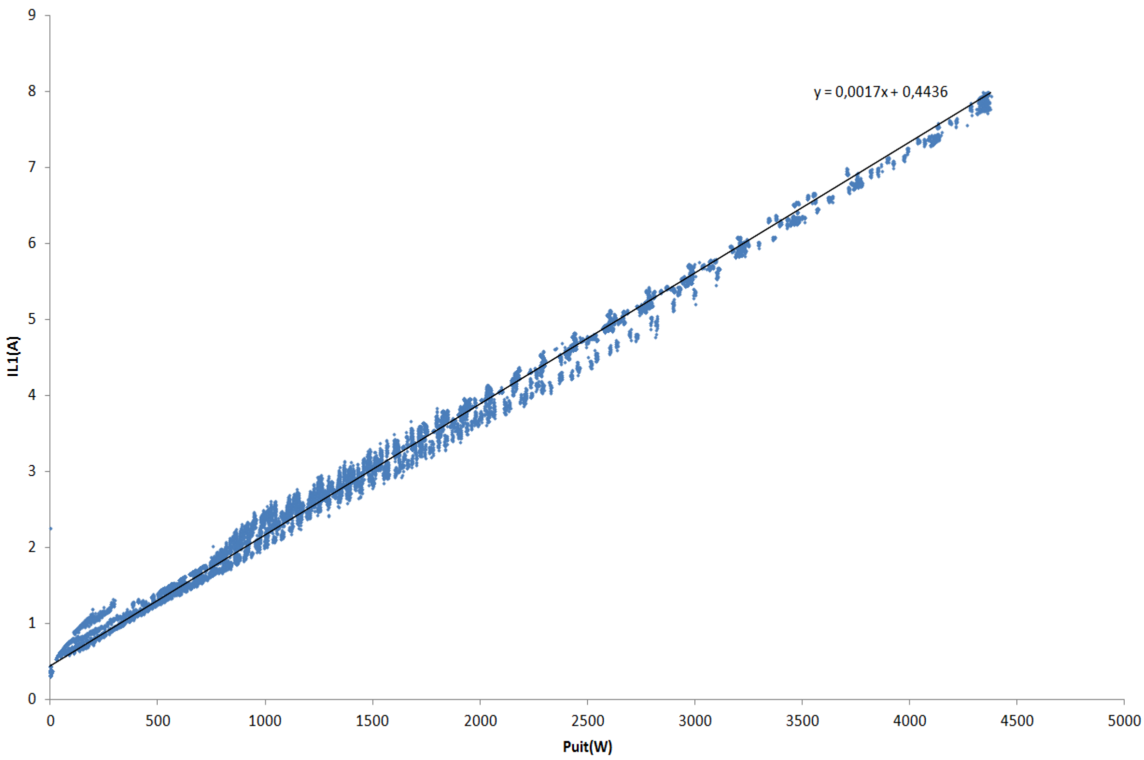


Fig. 5.6: Input Current VS Output Power

Tests 1 and 2 (see Annexes F and G) have shown that the following formula applies:

$$I_L = a\,P_{out} + b \quad \ldots.(5.3)$$

For example, because the line current IL through P_{out0} and P_{out1} is obtained, the following applies:

$$I_{L1} = I_{L1}\,f(P_{out0}) + I_{L1}\,f(P_{out1}) \quad \ldots.(5.4)$$

Then the following relationships apply:

$$I_{L1} = a_0\,V_{out0}\,I_{out0} + b_0 + a_1\,V_{out1}\,I_{out1} + b_1 \quad \ldots.(5.5)$$

$$I_{L2} = a_0\,V_{out0}\,I_{out0} + b_0 + a_2\,V_{out1}\,I_{out2} + b_2 \quad \ldots.(5.6)$$

$$I_{L3} = a_0\,V_{out0}\,I_{out0} + b_0 + a_3\,V_{out1}\,I_{out3} + b_3 \quad \ldots.(5.7)$$

In which a (0 $_{t/m}$ 3) and b (0 $_{t/m}$ 3) should be determined experimentally.

There is a clear relationship between the line current and the output power. In formulas 5.5, 5.6, and 5.7, the constants a and b have a value that depends on the slope of the same graph. There are three phases (L1, L3, L3) and thus three different slopes depending on the values a and b.

To calculate the values of a and b, the relationship must be determined experimentally based on previous tests (test 1, 2 and 3).

In the final system, there are 3xTDK-HWS 1500-24 connected in parallel and 3xTDK-HWS1000-15 loose (1000W-15V). A prototype ICCP has been made of this system. The theoretical results are verified on the basis of the measurements for this prototype ICCP. The input current limit processing is performed through the software. The relationships will therefore have to be recorded mathematically in a formula.

The derivation is developed for I_{L1}.

- 3 parallel TDK-HWS-HWS's of 1500-24: there is no limit.
- 3 loose TDK-HWS1000-15: there are limits.

- ***Controller settings:***

$I_{L\text{-}max:}$ the maximum input current

$P_{out\text{-}max}$: the maximum output power

$V_{out\text{-}max:}$ the maximum output voltage

$I_{out\text{-}max}$: the maximum output current

- ***Parameter controller***

$P_{out\text{-}act:}$ the current output power

$V_{out\text{-}act:}$ the current output voltage

$I_{out\text{-}act}$: the actual output current

- ***Scheme of controller***

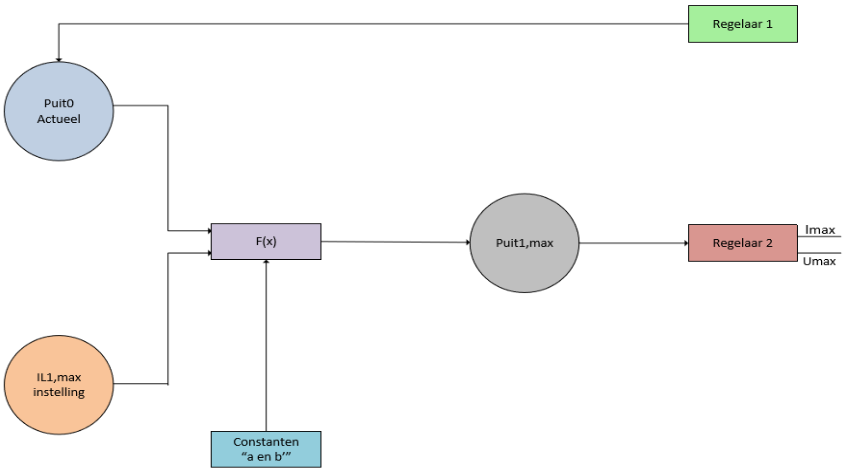


Fig. 5.7: Block diagram of boundary of IL1

De 3 parallel TDK-HWS-HWS's of HWS1500-24 are not limited.

The maximum value of P_{out0} should not therefore cause more line current than $I_{L1,\ max}$, because the line current should not be exceeded. The following applies to the maximum line current as a result of $P_{uit0,\ max}$:

$$\boldsymbol{I_L = a_0\ P_{out0,max} + b_0}\ \ldots(\mathbf{5.8})$$

Then applies to $P_{out\text{-}max}$:

$$\boldsymbol{P_{out0,max} < \frac{1}{a_0}\ I_{L1,max} - \frac{b_1}{a_1}}\ \ldots(\mathbf{5.9})$$

By substitution of $(P_{out} = V_{out}I_{out})$ in the formula 5.5, the following is obtained:

$$\boldsymbol{I_{L1} = a_0\ P_{out0} + b_0 + a_1\ P_{out1} + b_1}\ \ldots(\mathbf{5.10})$$

Then is P_{out} the current value, where applies the $P_{out0} < P_{out0,max}$ The 3 losse TDK-HWS1000-15 are limited. Fill in 5.10 provides the following formula:

$$\boldsymbol{I_{L1,max} = a_0 + b_0 + a_1\ P_{out,max} + b_1}\ \ldots.(\mathbf{5.11})$$

Describe to $P_{out1,\ max,}$ provides:

$$P_{out1,max} = \frac{a_0}{a_1} P_{out0,act} + \frac{I_{L1,max}}{a_1} - \frac{b_0}{a_1} - \frac{b_2}{a_1} \dots (5.12)$$

In the same way the formula is for the Pout3-max and $P_{out3-max}$ adjusted. Then the following formulas apply:

$$P_{out2,max} = \frac{a_0}{a_2} P_{out0,act} + \frac{I_{L2,max}}{a_2} - \frac{b_0}{a_2} - \frac{b_2}{a_2} \dots (5.13)$$

$$P_{out3,max} = \frac{a_0}{a_3} P_{out0,act} + \frac{I_{L3,max}}{a_3} - \frac{b_0}{a_3} - \frac{b_3}{a_3} \dots (5.14)$$

5.4.3: Determination of current curve

The parameters determine the graphs of current versus power output, see Appendix K – Results and graphs of Test 4 and Appendix K – Results and graphs of Test 5.

The values of parameters (a0 t/m b3) are:

a0	b0	a1	b1	a3	b3	a3	b3
0.0017	0.4436	0.00056	0.116	0.00056	0.12	0.0006	0.09

Table 5.4: The values of parameters

Below are the formulas of $P_{out-max}$:

$$P_{out0,max} < \frac{1}{0.0017} I_{L1,max} - 207 \quad \dots (5.15)$$

$$P_{out1,max} = -3.036\, P_{out0,act} + \frac{I_{L1,max}}{0.00056} - 1000 \quad \dots (5.16)$$

$$P_{out2,max} = -3.36\, P_{out0,act} + \frac{I_{L2,max}}{0.00056} - 1006 \quad \dots (5.17)$$

$$P_{out3,max} = -2.83\, P_{out0,act} + \frac{I_{L3,max}}{0.0006} - 890 \quad \dots (5.18)$$

In which $P_{out-max}$ is the dynamic setting, $I_{L,max}$ is the fixed setting values and $P_{out-act}$ is the current value.

5.4.4: Sub- conclusion

- The graph of IL vs Pout is the most important for determining the current limit.
- The formulas of the current limitation have been determined.

5.5: Measurement results: Prototype ICCP test

5.5.1: Description of the cabinet

Fig. 5.8: The prototype ICCP of the measuring and control box

- The net weight of the cabinet is 320 kg.
- The cabinet cannot be lifted by the fixing eyes.
- Slowly and carefully lift straight up.
- There should be 300mm of free space around the cabinet. There should be space to open the entry.

5.5.2: Dimensions in mm.

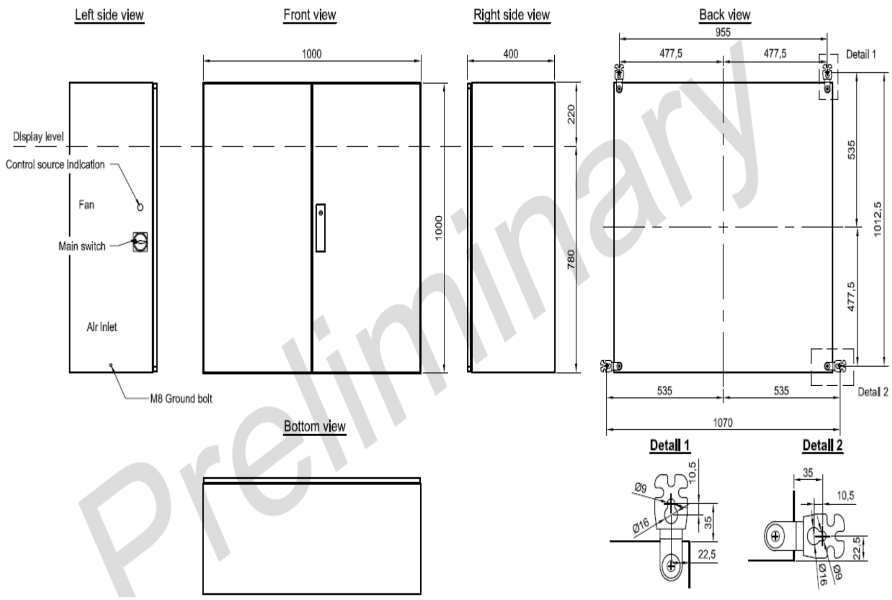


Fig. 5.9: The dimensions of the cabinet

6: Design and simulation of filter for ICCP

6.1: Introduction

The purpose of designing the filter is to limit the emission of unwanted harmonics (2 - 40 harmonics). There are active and passive filters. It must be analysed which output is most suitable: the low-, high- or band-pass filter. At the same time, the frequency behaviour must be studied. Then it is determined which design is suitable and which formula of the system can be used. Finally, a MATLAB simulation has to be done.

6.2: Design filter

The purpose of designing the filter is to limit the emission of unwanted harmonics (2 - 40 harmonics).

6.2.1: Passive and active filters

Filters are a class of electronic circuits in signal processing which allow or block a desired signal range or signal. Filters can be divided into many levels based on their properties, such as active - passive, analog - digital, linear - nonlinear, discrete time - continuous time, time invariant and time variant.
In general, there are active and passive filters. Active and passive filters are distinguished by the passivity of the components used in the filter circuit. If a component current is used then it is a passive component.
The benefits of each filter type:

Passive filter	Active filter
No power supply required	No coils
Can handle large currents, high voltages	Easier to design
Very reliable	High Z_{in}, low Z_{uit} for minimum load
Noise arises from resistors	Easier to set up
No bandwidth limitation	Small size and weight

Table 6.1: Benefits of active and passive filters

The disadvantages of each filter type:

Passive filter	Active filter
Inductors large for lower frequencies	Power required
Limited standard sizes	Sensitive to intermodulation, oscillations
Low tolerance inductors (1-2%), very expensive	Sensitive to parasitic voltage from DC output offset voltage and input bias currents
Generally, not amenable to miniaturization	Opamp gain bandwidth limited
No power gain possible	Slew rate limited opamp
No voltage gain	Many components needed

Table 6.2: Disadvantages of the filter active and passive filters

6.2.2: Frequency behaviour filter

Because passive filters can handle large currents and high voltages and are also very reliable, and they also take less time to design, it is decided to design a passive filter.

There are different filter types.

High and Low Pass Filters

A high-pass filter allows the high part of the frequency spectrum to pass, a low-pass filter the low part

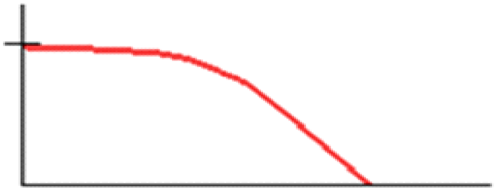


Fig. 6.1: Low -pass filter

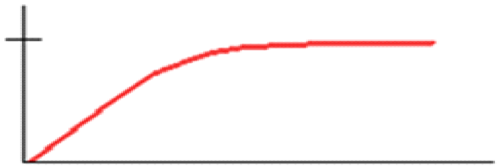


Fig. 6.2: High pass filter

Features of these types are:

he cut-off frequency, determines from which frequency the filter cuts/passes the rest of the spectrum. In the case of a low pass filter, the part of the spectrum that is removed becomes smaller as the frequency increases. With low and high pass filters, this frequency marks the point where -3 dB attenuation occurs. This point is also known as the -3 dB point. The filter does not resolutely cut off part of the spectrum, because there is a transition region. It is usual that from the cut-off frequency the amplitude factor halves per frequency doubling or halving.

Band-Pass Filter

A band is another word for frequency range. A band-pass filter allows a part in the middle of the spectrum to pass. This type of filter is the core of a radio and television receiver.

This type can be constructed by combining a low-pass and high-pass filter. This creates two 3 dB points.

Characteristics of these types are:

The centre frequency (f1 and f2). This is similar to the cut-off frequency.

The bandwidth or quality (Q-factor). This indicates how wide the tire is to be passed or removed. The Q factor is calculated by dividing the centre frequency by the distance between the frequencies of both-3 dB points.

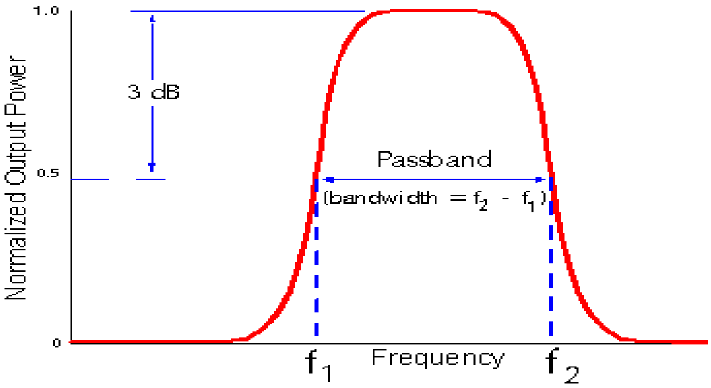


Fig. 6.3: Bandpass filter

6.2.3: Filter selection

A simple first-order passive filter can be made by connecting a resistor and capacitor in series, between an input signal (Vin) and the output of the filter (Vout). The path connecting the resistor and capacitor with respect to the output signal determines the type of filter construction: either a low pass filter and a high pass filter.

A simple passive RC low pass filter LPF is made by connecting a resistor in series with a capacitor as shown below. In such filter arrangement, the input signal (Vin) is added to the series connection (resistor and capacitor together), but the output signal (Vout) is only taken from the capacitor.

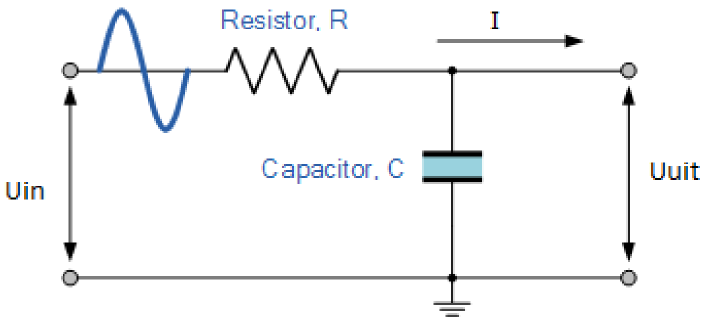


Fig. 6.4: Low pass filter circuit

The reactance of a capacitor is inversely proportional to its frequency; the value of the resistance remains constant as the frequency changes. At low frequencies, the capacitive reactance (Xc) of the capacitor is very large compared to the resistance value of the resistor R. This means that the voltage potential Vc across the capacitor is much greater than the voltage drops Vr. At high frequencies, the reverse is true for Vc (small) and Vr (large) due to the change of the capacitive reactance value.
Although the above circuit is that of an RC low pass filter circuit, it can also be considered as a controllable voltage divider circuit. The following formula is used to calculate the output voltage of two single resistors in series:

$$\boldsymbol{Vout = Vin\frac{R1}{R1 + R2}} \ldots (\mathbf{6.1})$$

The impedance Z in a series connection of a resistor with a capacitor is calculated:

$$\boldsymbol{Z = \sqrt{R^2 + X_c^2}} \ \ldots (\mathbf{6.2})$$

Then substituted in formula 6.1:

$$\boldsymbol{Vout = Vin\frac{X_c}{Z}} \ldots (\mathbf{6.3})$$

The capacitive reactance of a capacitor in an AC circuit AC is:

$$\boldsymbol{X_c = \frac{1}{2\pi fc}} \ldots (\mathbf{6.4})$$

The relationship between input and output voltage is now clear.

6.2.4: Design low pass filter

The cut off frequency of the lowpass filter:

$$\boldsymbol{f_c = \frac{1}{2\pi RC}} \ldots (\mathbf{6.5})$$

In which are:

$$\tau = R\,C \ldots (6.6)$$

The values of τ, R and C, determine the different frequencies:

Fc (Hz)	T(Sec)	R ()	C(µF)
50	0.00318	2	1590
175	0.0009095	2	454
250	0.0006366	2	318

Table 6.3: R en C values

The slope of the cut-off frequency increases in the second order of the low pass filter. The 3dB frequency of the second order of the low pass filter is:

$$\boldsymbol{f(-3db) = f_c\sqrt{2^{\frac{1}{2}} - 1}} \ldots (\mathbf{6.7})$$

Whereby:

f_c is the cut-off frequency.
n is the order of filter.

6.2.5: Mathematical basis of harmonic currents

From the measurement results of the prototype ICCP, a graph is obtained that determines the formula of the harmonic currents.

The odd harmonic values from 3 to 39 are drawn by the results measured in the input current, I_{1h}=9,11A (I_{L1} =9,25 A).

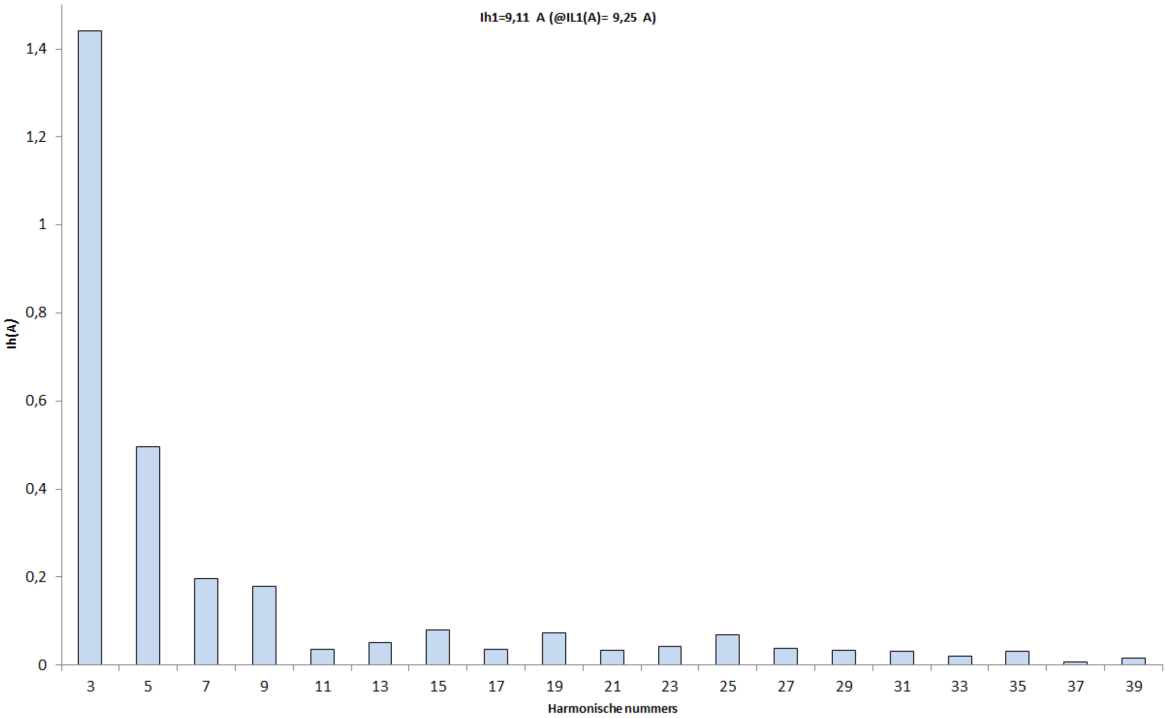


Fig. 6.5: Harmonic results of 3 -39

The total input current is:

$$IL^2 = I1\_h^2 + I2\_h^2 + I3\_h^2 + I4\_h^2 + \cdots + I40_h{}^2 \quad \ldots (6.8)$$

At which:

I1_h = fundamental current = 9.11 A

Irest_h = the rest harmonic currents= 1.44 A, 0.48 A, 0196 A…

6.3: Simulation

6.3.1: Simulation of the system

The aim of the simulation is to design the low pass filter to minimize the current harmonics (@f=100 and 150, 200 Hz etc.).

Not all harmonics current is used. Only the 3rd, 5th and 7th are used because the even harmonic current and the rest of the harmonic current are about zero. See Fig. 5.3.

The formula (6.7) becomes:

he mathematical formula (6.8) is used as a basis in the simulation. In the simulation, the cut-off frequency of the low-pass filter is designed as 50 Hz, 1st order- 175 Hz and 2d order- 250 Hz.

	I3(A)	I5|(A)	I7(A)	Ihtot. (A)	THD I
Without LPF	1.44	0.49	0.19	0.18	17%
The system with LPF 1st order- fc= 175 Hz	1.09	0.29	0.09	0.07	13%
The system with LPF 2d order- fc= 250 Hz	1.01	0.19	0.05	0.04	12%

Table 6.4: Compare between different simulations

Using LPF 2d order - fc=250 Hz is the best result because the THD I get (12%), but the filter is 2d order needs more components. See figure 6.6:

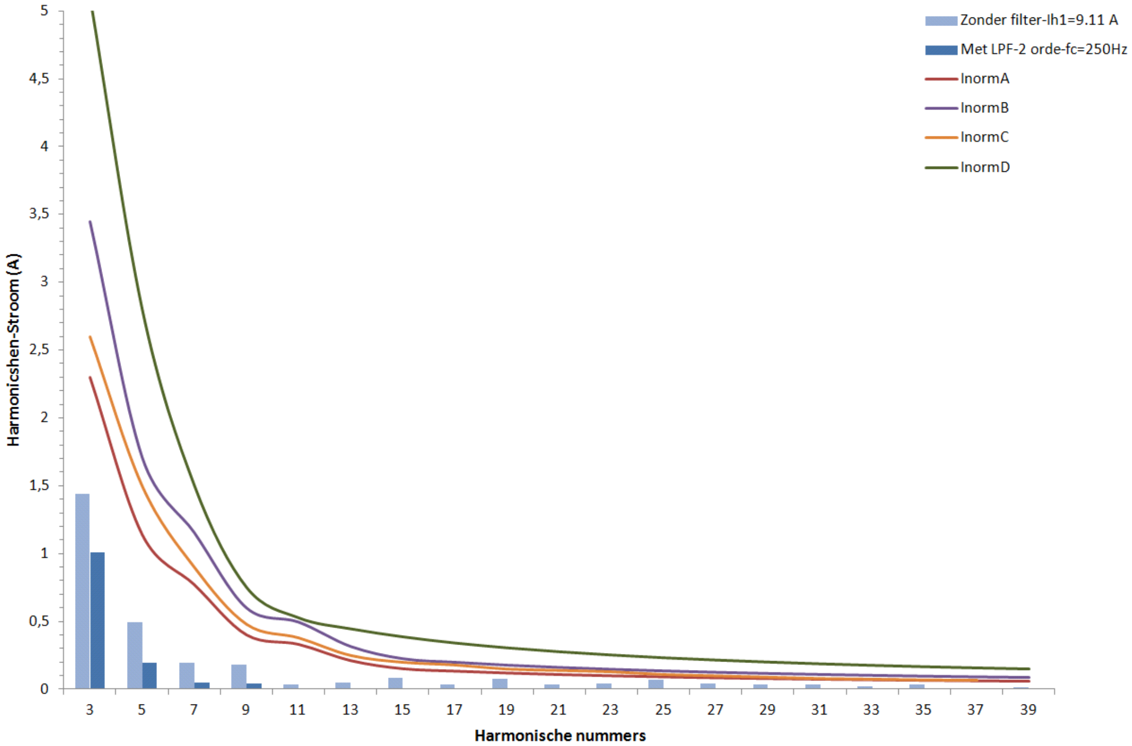


Fig. 6.6: Compare between harmonic current with and without filter

6.3.2: The system without filter

```
%%How to apply FFT on acurrent harmonica
% Significance.

sampling = 10000;           %Sampling Frequency
tSampling = 1/fSampling;    %Sampling Time
L = 10000;                   %Length of Signal
t = (0: L-1) *tSampling;    %Time Vector
F = 50;                      %Frequency of Signal
%% current harmonicas
xsig =
9.11*sin(2*pi*F*t)+1.44*sin(6*pi*F*t)+0.497*sin(10*pi*F*t)+0.196*sin(14*pi*
F*t)+0.179*sin(18*pi*F*t);
%%Frequency Transform of above Signal
subplot(1,1,1)
```

```
NFFT = 2^nextpow2(L);
Xsig = fft(xsig,NFFT)/L;
f1 = fSampling/2*(linspace(0,1,NFFT/2+1));
semilogy(f1,2*abs(Xsig(1:NFFT/2+1)),'r');
grid on;
axis([0 500 1.0000e-001 10])
title('Spectrum of the system without filter');
xlabel('\itFrequency(Hz) \rightarrow');
ylabel('|Amplitude| \rightarrow');
pause(2);
```

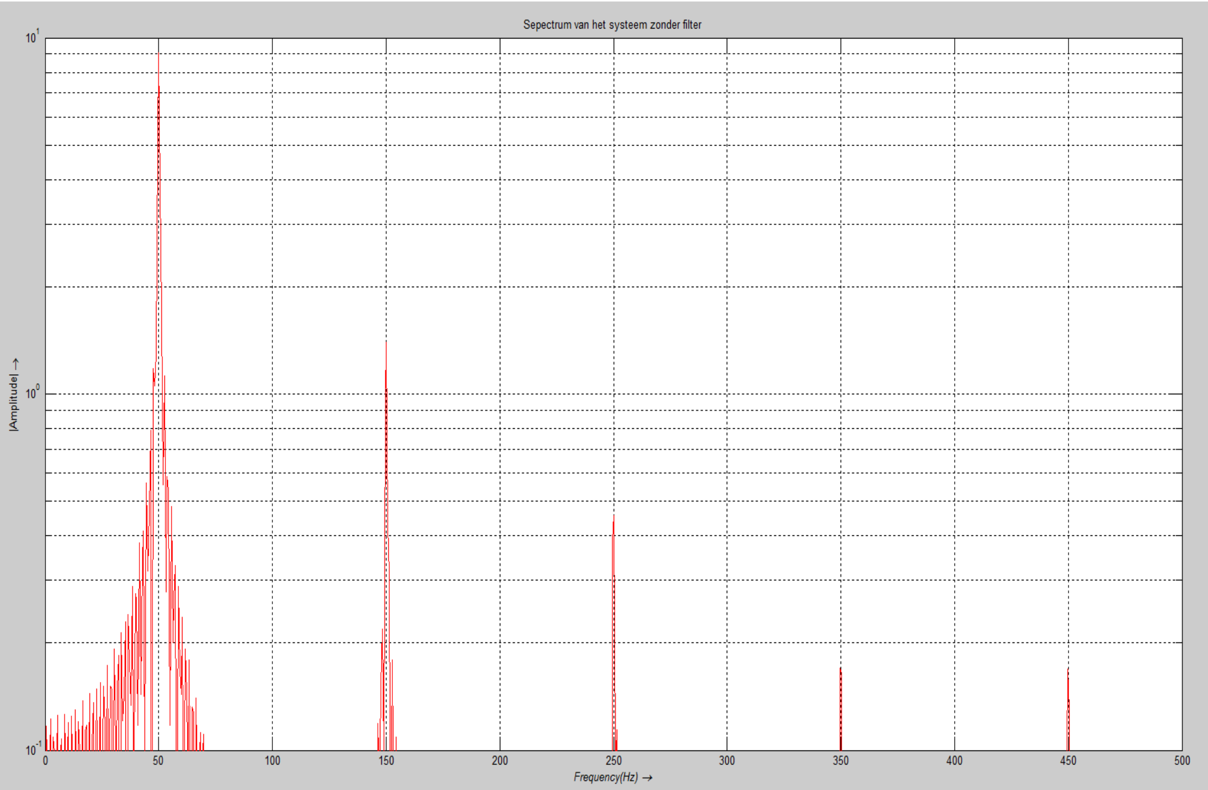


Fig. 6.7: Spectrum of current harmonics of the system without filter

6.3.3: The system with filter- 1st order- 50Hz

- *Filter fc =50 Hz*

```
%%How to apply LPF fc=50Hz
s = tf('s');
subplot (1,1,1)
a=0.00318;
LP = 1/(1+a*s);
bodeplot (LP);
```

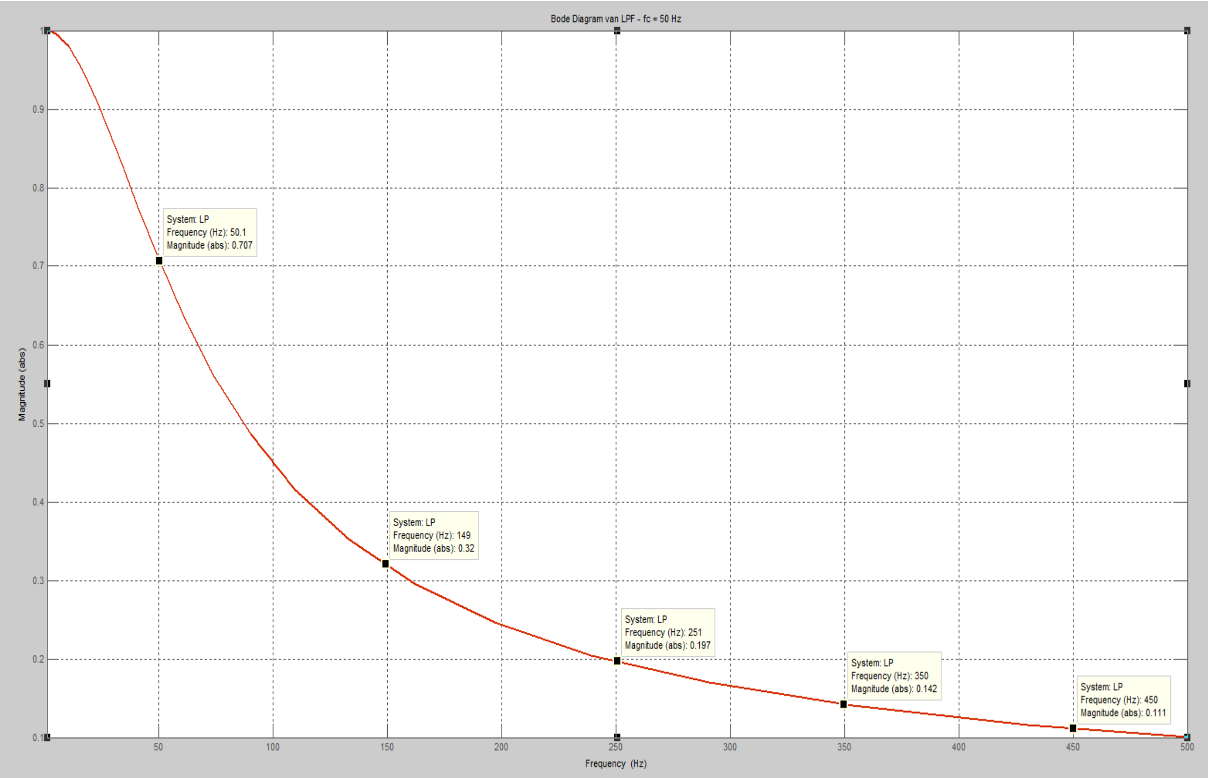


Fig. 6.8: Bode diagram of LPF – fc=50 Hz

6.3.4: Spectrum of the system filter fc=50Hz

```
%%This Project shows how to apply FFT on a signal and its physical
% Significance.


fSampling = 10000;            %Sampling Frequency
tSampling = 1/fSampling;    %Sampling Time
L = 10000;                    %Length of Signal
t = (0:L-1)*tSampling;        %Time Vector
F = 50;                      %Frequency of Signal
%% Signal
xsig = 9.11*sin(2*pi*F*t)
+1.44*sin(6*pi*F*t)+0.497*sin(10*pi*F*t)+0.196*sin(14*pi*F*t)+0.179*sin(18*
pi*F*t);
%%Frequency Transform of above Signal
subplot (2,1,1)
NFFT = 2^nextpow2(L);
Xsig = fft(xsig,NFFT)/L;
f1 = fSampling/2*(linspace(0,1,NFFT/2+1));
semilogy (f1,2*abs (Xsig(1:NFFT/2+1)),'r');
Grid on;
axis ([0 500 1.0000e-001 10])
Title ('Spectrum of the system without filter');
xlabel('\itFrequency(Hz) \rightarrow');
```

```
ylabel('|Amplitude| \rightarrow');
pause(2);
s = tf('s');
subplot(2,1,2)
a=0.00318;
LP = 1/(1+a*s);
bodeplot(LP);
```

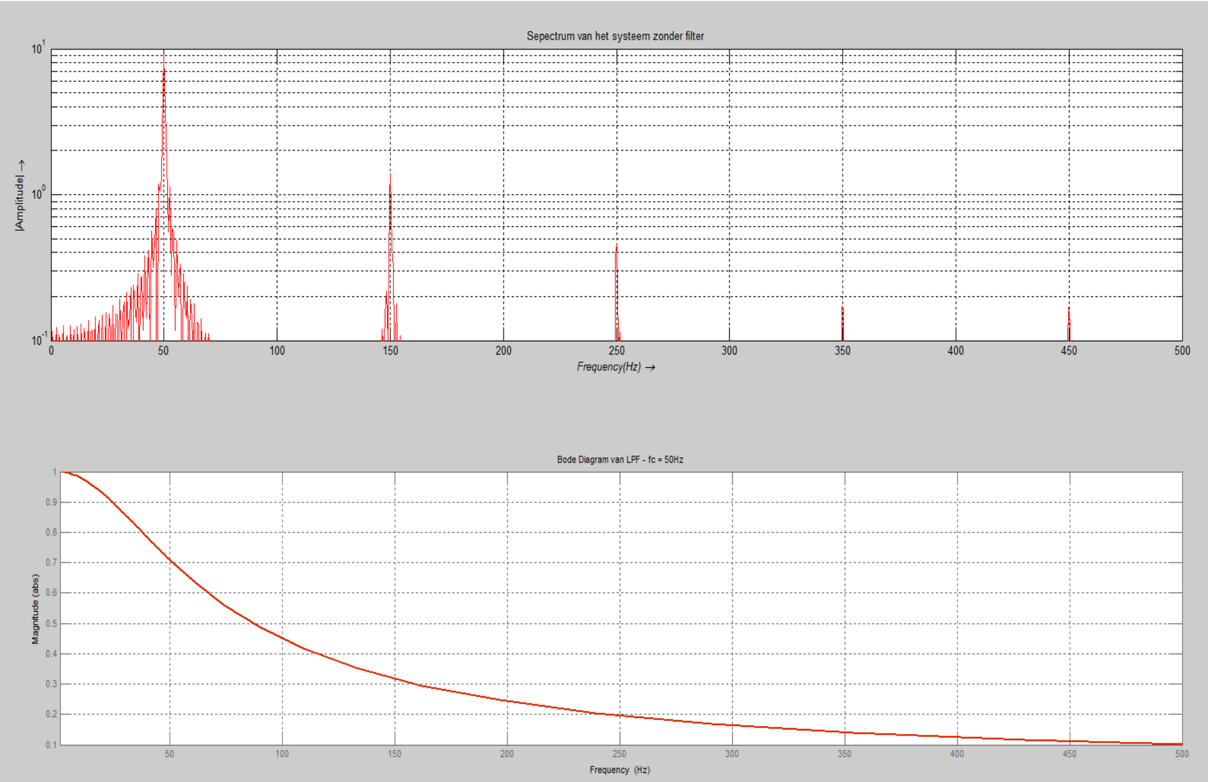


Fig. 6.9: Spectrum of current harmonics without filter and bode diagram of LPF – fc=50 Hz

- ***The system with LPF- 1St order- fc=50Hz***

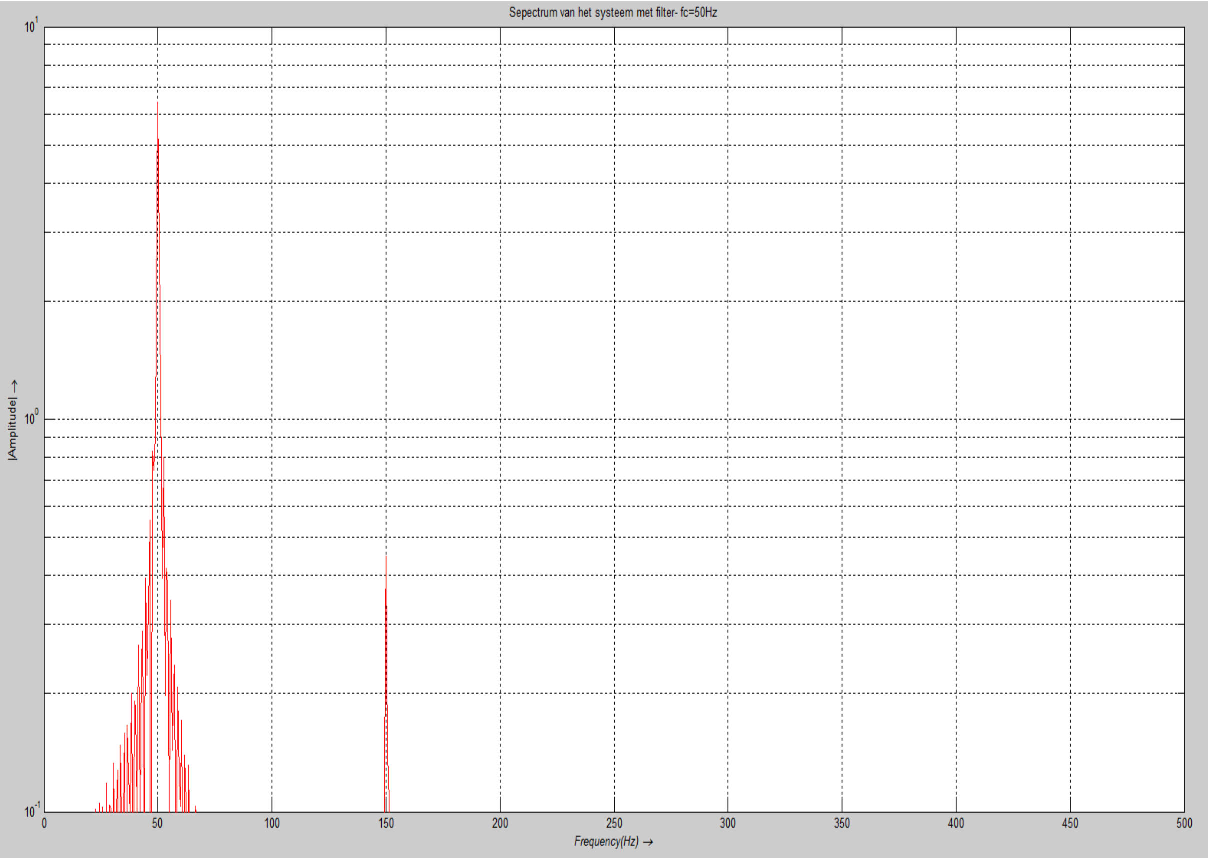


Fig. 6.10: Spectrum of current harmonics of the system with LPF fc=50Hz

6.3.5: The system with filter- 1St order- 175 Hz

- ***Filter fc =175 Hz***

```
%%How to apply LPF fc=175Hz
s = tf('s');
subplot(1,1,1)
a=0.0009095;
LP = 1/(1+a*s);
bodeplot(LP);
```

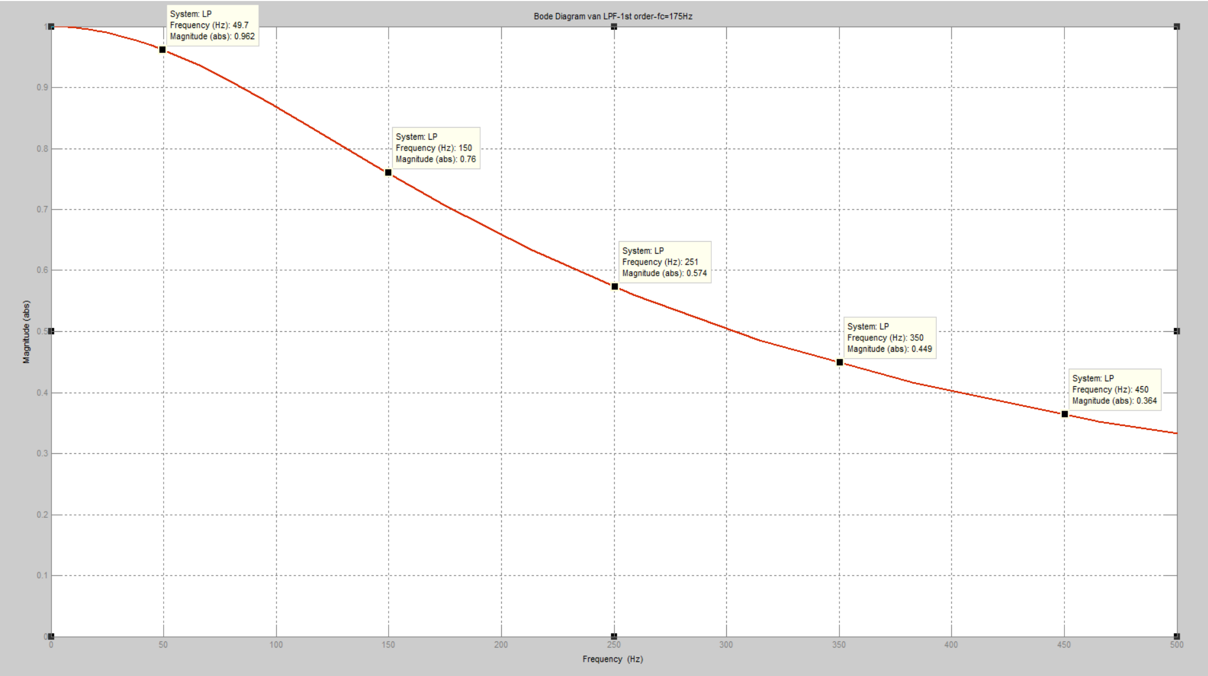


Fig. 6.11: Bode diagram of LPF – fc=175 Hz

- ***The system with LPF- 1St order- fc=175Hz***

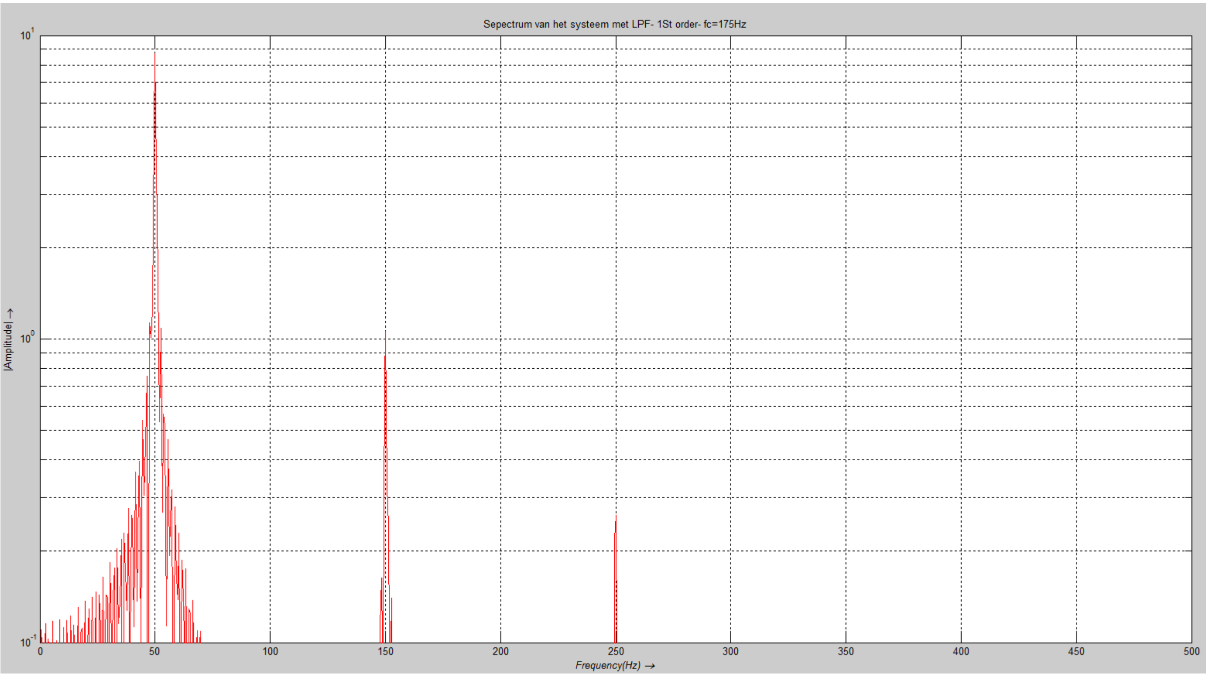


Fig. 6.12: Spectrum of current harmonics of the system with LPF fc=175 Hz

6.3.6: The system with filter- 2d order- fc=250 Hz Filter fc =250 Hz

```
%%How to apply LPF-2d order- fc=250Hz
s = tf('s');
subplot(1,1,1)
a=0.0006366;
LP = 1/(1+a*s)*1/(1+a*s);
bodeplot(LP);
```

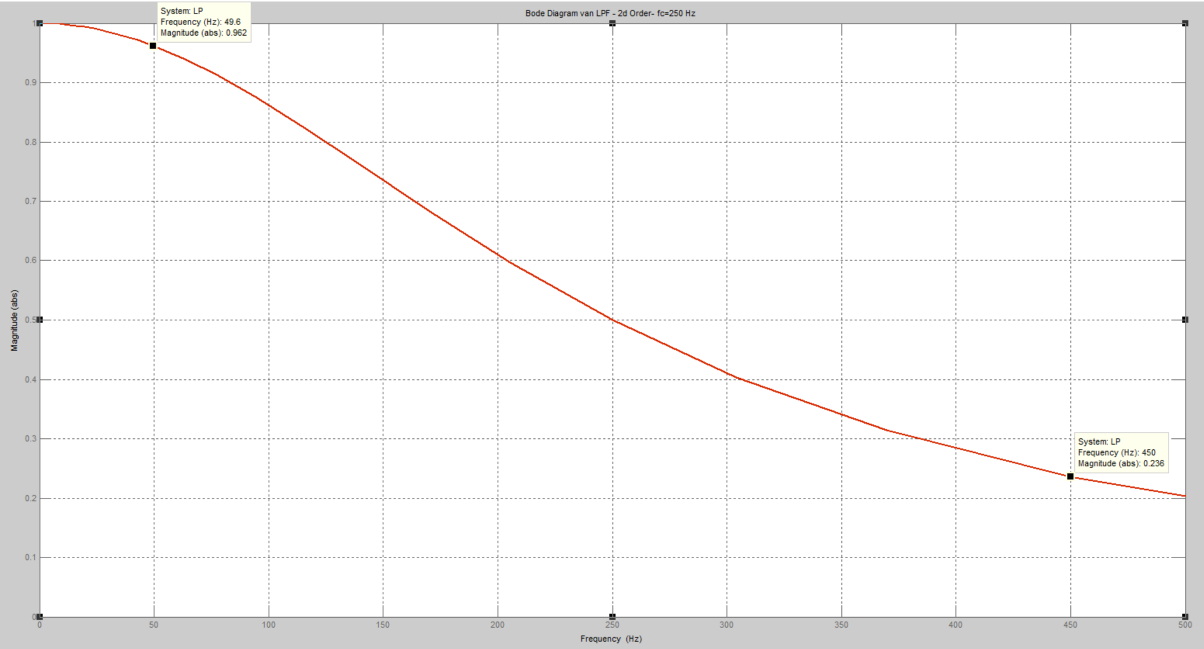


Fig. 6.13: Bode diagram of LPF –2 d order - fc=250 Hz

- *The system LPF – 2d order- fc =250 Hz*

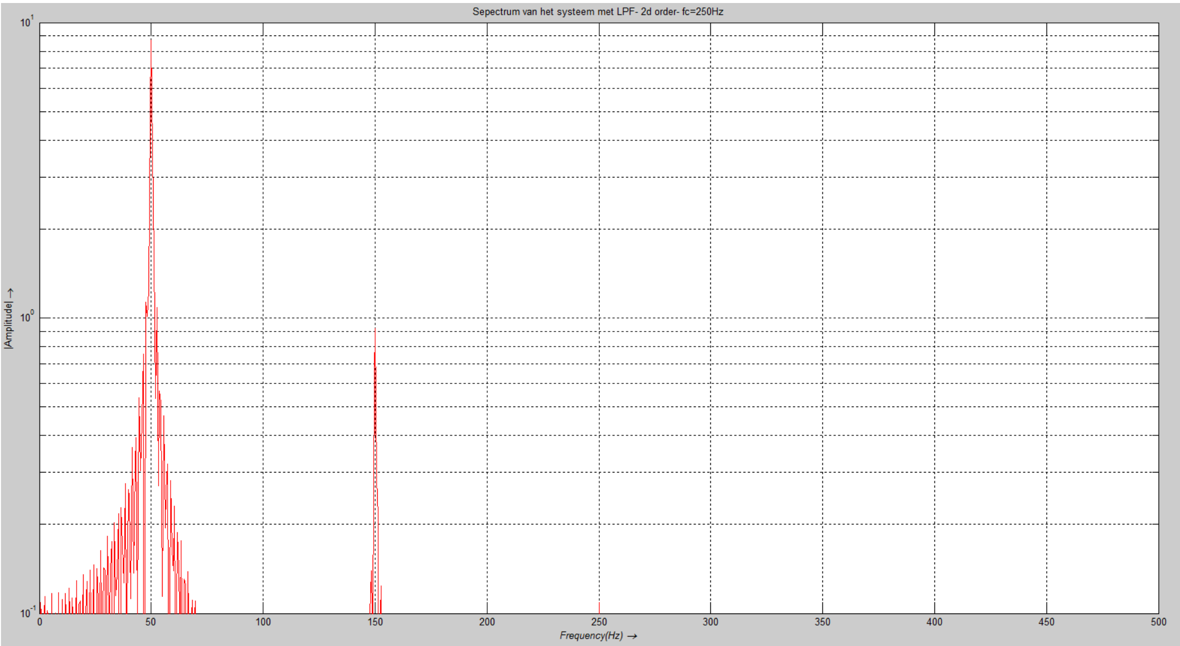


Fig. 6.14: Spectrum of current harmonics of the system with LPF- 2d order fc=250Hz

6.4: Sub- conclusion

A graph is obtained from part of the measurement results, which determines the formula of the harmonic current.
LPF is used with the measurement and control box to reduce current harmonics.

LPF – 2d order- fc=250 Hz is the best result used with the cabinet.

7: Conclusion and recommendations

7.1: Overall conclusion

1, The prototype of the measurement and control box ICCP have been analysed, designed and tested.

- The connections of the measurement and control cabinet have been schemed.
- The components of the measurement and control box have been selected and connected.
- The electrical diagram has been drawn.
- The components of the ICCP are submitted to a risk analysis and a service life determination.

2. The measurement and control box ICCP comply with immunity, emission and harmonic standards.

- Immunity and emissions test results are obtained from the manufacturer's AC/DC conversion datasheets (TDK-Lambda).
- After literature research, it was found that all results fell within the limit values and they were therefore satisfactory.
- The measurements on the harmonic have been carried out.
- The harmonic complies with CE/IEC regulation.
- The class of the cabinet was determined.
- It is determined that the harmonic disturbance is lower than class A, it is the strictest class.

3. The test set-up of the measuring equipment has been achieved, as well as the test set-up of the variable load.

- The data logger has been used to measure all parameters simultaneously.
- A measurement per 1 load resistance lasted 55 seconds, whereas 27 different values of resistance are used with 40 voltage steps (0.5 V from 24V to 5V) which means one test takes 16.5 hours.
- The different values of the variable load were optimized by applying various parallel circuits.
- 27 steps were used in testing to achieve a higher resolution.
- The automatic measurement is done to save time. This was achieved by means of using a Mitsubishi PLC (hardware) and the Alpha 2 program (software).

4. A prototype of ICCP was carried out using the test set-up.

- The harmonic measurement results indicate to compliance of the CE/IEC standards.

5. The measurements (If and Pout) used to determine the input current limitation of the prototype, were worked out using the test setup.

- The relationship between the output power and the input current is derived in formula form.
- It has been found that the input current does not exceed 16 A.

6. A simulation model of the harmonic currents was achieved and based on the measurement results.

- This model has been used to simulate the effectiveness of the filter in MATLAB.
- It was determined whether it would be better to use active or passive filters.

7.2: Recommendations

1. It is recommended to determine the imbalance in phase currents.
2. It is also recommended to adapt the created test setup so that it can be used for other measuring and control cabinets.
3. It is recommended that the rating charts in this assignment will be standardized.
4. It is lastly recommended to investigate whether lightning protection is necessary

References

[1] Manual ICCP - AKBv3 Impressed Current Cathodic Protection System

[2] International Journal of Power Electronics and Drive System (IJPEDS), Vol. 11, No. 1, March 3030

[3] IOP Conf. Series: Materials Science and Engineering 414 - 013034, ICAET, 3018

[4] "Identification and Control of Impressed Current Cathodic Protection System", Vol.13 No.3, 3016

[5] http://www.dare.nl/informatie/organisatie

[6] NEN-EN-IEC 61000-6-3: en, fr, Elektromagnetische compatibiliteit (EMC) - Deel 6-3: Algemene normen - Immuniteit voor industriële omgevingen, 2006

7 NEN-EN-IEC 61000-6-4: en Elektromagnetische compatibiliteit (EMC) - Deel 6-4: Algemene normen - Emissienorm voor industriële omgevingen, 2011

[8] CISPR 16-3-1: en Specificatie voor meetontvangers en meetmethoden voor radiostoringen en -immuniteit - Deel 3-1: Methode voor het meten van storingen en immuniteit - Geleide storingsmetingen, 2010

[9] CISPR 16-1-3: en Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-3: Radio disturbance and immunity measuring apparatus - Coupling devices for conducted disturbance measurements (Redline version with track changes), 2014

[10] Compliance Testing to the IEC 61000-3-3 (EN 61000-3-3) and IEC 1000-3-3 (EN 61000-3-3) Standards

[11] HWS 1500 Series- Instruction Manual- Densi-Lambda-2009

[12] FieldLogger, Instruction manual, Novus

[13] DT80 Range DT80/81/83/85 Series 1, 3 & 3 Includes CEM30 User's Manau

[14] http://www.euro-index.nl/nl/klantenservice/euroinfo/netvervuiling-harmonischen/

15 HWS- 1000-Test Data ICE-61000 series, Densei-Lambda, P.R-3, 4, 5 en 7 18

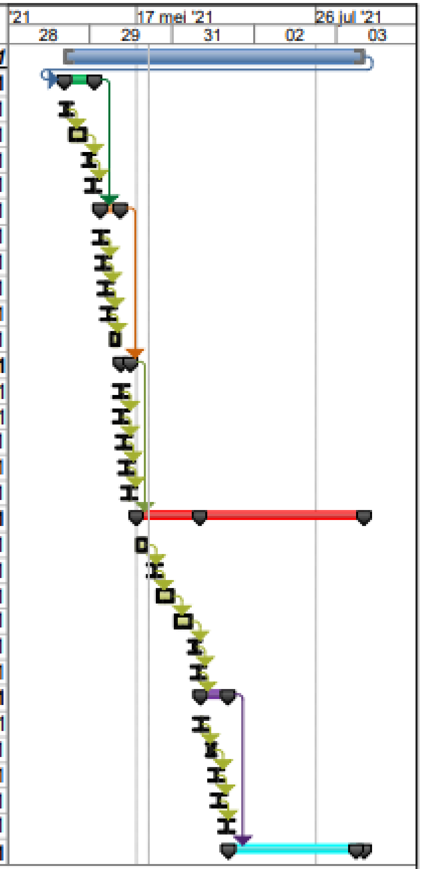
16 HWS - 1500-Test Data ICE-61000 series, Densei-Lambda, P.R-3, 4, 5 en 7

17 WS1000- Evaluation Data-2008

18 HWS1500- Evaluation Data-2008

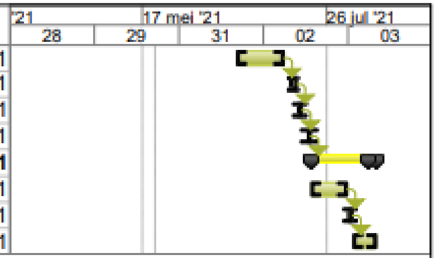
Appendix A- Expected plan of the project

Id		Task Name	Duur	Begindatum
1		***GRADUATION PROGRAM***	**85 dagen**	***maa 19/04/21***
2		**Plan of steps**	**10 dagen**	**maa 19/04/21**
3		Drawing up a plan of action	2 dagen	maa 19/04/21
4		Initialize the proposed project	5 dagen	woe 21/04/21
5		approved plan	2 dagen	woe 28/04/21
6		Completion of the plan	1 dag	vri 30/04/21
7		**Phase 1: The CE Standard**	**6 dagen**	maa 03/05/21
8		Iimmunity: standard IEC 6100-4-2, IEC 6100-4-6, IEC 6100-4-11, IEC 6100-4-5, IEC 6100-4-4	1 dag	maa 03/05/21
9		Fast transients Test (IEC61000-4-4)	1 dag	din 04/05/21
10		Surge Immunity Test (IEC61000-4-5)	1 dag	woe 05/05/21
11		Emission: Standards IEC 6100-6-4	1 dag	don 06/05/21
12		Harmonic:Standards IEC 61000-3-2	2 dagen	vri 07/05/21
13		**Phase 2: Electrical schematic**	**4 dagen**	**din 11/05/21**
14		Property of input:	4 uur	din 11/05/21
15		Property of output	4 uur	din 11/05/21
16		Components	1 dag	woe 12/05/21
17		Assemble and install	1 dag	don 13/05/21
18		Completion of phase 2	1 dag	vri 14/05/21
19		**Phase 4: limitation and programing PLC**	**19 dagen**	**maa 17/05/21**
20		Tests and measurements	5 dagen	maa 17/05/21
21		Programing the PLC	1 dag	maa 24/05/21
22		The relationship between the output current, efficiency and graphic	5 dagen	din 25/05/21
23		The relationship between the output current and the cos and graph	5 dagen	din 01/06/21
24		The relationship between the output current and the input current	2 dagen	din 08/06/21
25		Completion of phase 4	1 dag	don 10/06/21
26		**Phase 5: Primary filter**	**7 dagen**	**vri 11/06/21**
27		Determining the situation without filter (zero situation)	1 dag	vri 11/06/21
28		Determine THD 1, THD 3	3 dagen	maa 14/06/21
29		Filter designs	1 dag	don 17/06/21
30		Determination of THD I, THD U according to standard 61000-3-2	1 dag	vri 18/06/21
31		Completion of phase 3	1 dag	maa 21/06/21
32		**Phase 6: Simulation**	**36 dagen**	**din 22/06/21**



Project: G:\1. Afstuderen andere\1. Pv
Date: zat 22/05/21

Id	Task Name	Duur	Begindatum
33	Build: A prototype has to be built	14 dagen	din 22/06/21
34	Deriving a new mathematical formula for the output power	3 dagen	maa 12/07/21
35	Minimize harmonic currents of the input filter	2 dagen	don 15/07/21
36	Matlab simulation	1 dag	maa 19/07/21
37	**Dissertation**	**16 dagen**	**din 20/07/21**
38	Drafting concept	10 dagen	din 20/07/21
39	Improved Draft Report Submission	2 dagen	din 03/08/21
40	Written defense	7 dagen	don 05/08/21



Project: G:\1. Afstuderen andere\1. Pv
Date: zat 22/05/21

Task | Split | Milestone | Summary | Project Summary | External Tasks | External Milestone | Inactieve taken | Inactieve mijlpaal | Inactieve samenvatting | Handmatig taak | Alleen duur | Handmatige samenvatting | Handmatige samenvatting | Alleen begindatum | Alleen einddatum | Progress | Deadline

Table A.1: Expected Plan of the project

Appendix B - Immunity standard

1: Introduction

EMC is Electromagnetic Compatibility. EMC shows how an equipment behaves in relation to the electromagnetic environment, to what extent one equipment can affect another or vice versa. Immunity is the degree to which a device is resistant to electromagnetic radiation.

Typical sources include, for example, power lines, electronic circuits, electric motors, radio and radar transmitters. Equipment that is being disrupted, often referred to as 'victim' equipment by the EMC specialists, can consist of almost anything that uses EM energy, such as radio receivers, household appliances or electronic circuits of any kind. Concerning the immunity side, the purpose is to ensure that the equipment is not affected by, for example, radio transmissions, power supply disturbances, electrostatic fields or other phenomena.

2: Immunity Standard

2.1: Standard IEC 61000-6-3

This part of IEC 61000 for immunity requirements EMC applies to electrical and electronic equipment used in industrial environments. Immunity requirements in the frequency range from 0 Hz to 400 GHz is included.

<table>
<tr><th></th><th>Environmental phenomena</th><th colspan="2">Test specification</th><th>Units</th><th>Basic standards</th></tr>
<tr><td>4.1</td><td>Radio-frequency common mode</td><td colspan="2">0.15 to 80
10
80</td><td>MHZ
V
% AM (1KHZ)</td><td>IEC 61000-4-6</td></tr>
<tr><td rowspan="2">4.2</td><td rowspan="2">Voltage dips</td><td colspan="2">0
1</td><td>% Residual voltage cycle cycle</td><td rowspan="2">IEC 61000-4-11</td></tr>
<tr><td>40
10/12
At
50/60Hz</td><td>70
25/30
At
50/60Hz</td><td>% Residual voltage cycle</td></tr>
<tr><td>4.3</td><td>Voltage interruptions</td><td colspan="2">0
250/300 at 50/60Hz</td><td>% Residual voltage cycle</td><td>IEC 61000-411</td></tr>
<tr><td>4.4</td><td>Surges
line-to-earth
line-to-line</td><td colspan="2">1 .3/50 (8/30)
±2
±1</td><td>Tr/Th µs
KV (open circuit test voltage)
KV (open circuit test voltage)</td><td>IEC 61000-4-5</td></tr>
<tr><td>4.5</td><td>Fast transients</td><td colspan="2">±2
5/50
5</td><td>KV (open circuit test voltage)
Tr/Th ns
Repetition frequency kHz</td><td>IEC 61000-4-4</td></tr>
</table>

Table B.1: The maximum immunity limits according to IEC 61000-6-3

2.2: Limits

Table C.1 shows the maximum immunity limits according to IEC 61000-6-3 for 5 environmental phenomena:

1) Radio frequency common mode
2) Voltage dips
3) Voltage Interruptions
4) Overvoltage's (line-ground and line-line)
5) Fast transients

1. Radio frequency common mode

Noise in a cable, or transmitted from a cable, it usually occurs in common mode, i.e., the same signal is likely to be picked up by both of the conductors in a two-wire cable.

Limits for 0.15MHz to 80MHz

Standard: IEC 61000-4-6

Voltage limit: 10 V.

Limit amplitude modulated: 80% AM (1 kHz)

2. Voltage dips

Electrical and electronic equipment can be affected by voltage dips from the power supply. Voltage dips are caused by faults in the network or by a sudden large change in the load.

Limits for 0% Residual Voltage (100% rate of loss)

Standard: IEC 61000-4-11

Limit value cycle: 1 V.

Continuous Time: 5000ms

Limits for 40% Residual Voltage (60% degree of loss)

Standard: IEC 61000-4-11

Limit value cycle: 10/13 V.

Frequency limit: 50Hz / 60Hz

Continuous Time: 100ms

Limits for 70% Residual Voltage (30% degree of loss)

Standard: IEC 61000-4-11

Limit value cycle: 35/30 V.

Frequency limit: 50Hz / 60Hz

Continuous Time: 10ms

3. Voltage interruptions

Electrical and electronic equipment can be affected by short interruptions to the power supply. Errors in the network or a sudden large change in the load cause interruptions.

Limits for 0% Residual Voltage

Standard: IEC 61000-4-11

Limit value cycle: 350/300 cycle

Frequency limit: 50Hz / 60Hz

4. Overvoltage's

The purpose of this test is to find the reaction of the DUT under operational conditions with over-voltage, when switching-effects may occur at certain threat levels.

Limits for line-ground voltage = ± 3kV (open circuit test)

Standard: IEC 61000-4-5

Limit value Shockwaves (Tr / Th): 1.3 / 50 µs

Limits for line-line voltage = ± 1 kV (open circuit test)

Standard: IEC 61000-4-5

Limit value Shockwaves (Tr / Th): 8/30 µs

5. Rapid transients

The repetitive fast transient test is a burst test which consists of multiple fast transients coupled into the power, control, and signal ports of electrical and electronic equipment.

Limits for open circuit test voltage = ± 3kV

Standard: IEC 61000-4-5

Limit value Shockwaves (Tr / Th): 8/30 µs

3.3: Measurement method

1): Radio frequency common mode test (IEC 61000-4-6)

a) Used equipment

RF generator, RF AMP, network disconnection (CDN) [15, 16]

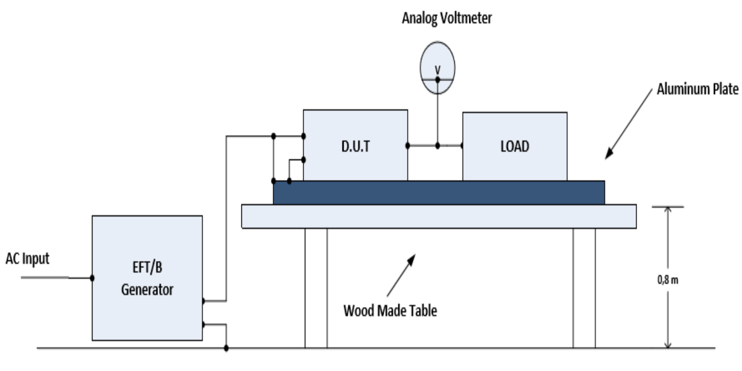


Fig. B.1: Guided Failure Test

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[15] **HWS- 1000-Test Data ICE-61000 series, Densei-Lambda, P.R-3, 4, 5 en 7 18**

[16] **HWS - 1500-Test Data ICE-61000 series, Densei-Lambda, P.R-3, 4, 5 en 7**

b) Test conditions

Input voltage: 230 V AC
Output current: 100%

Output voltage: nominal (15 V or 24)

Amplitude modulated: 1 KHz, 80%

Sweep condition: 1.0% step up, hold for 2.8 seconds

Electromagnetic Frequency: 150KHz-80MHz

Wave angle: horizontal and vertical

Test angle: top, bottom, both sides, front view, back view

Environment temperature: 25 degrees

c) Acceptable conditions

The output voltage regulation was not more than ± 5% of initial value (before test) during the test. output voltage should be in the output voltage regulation specification after the test.

along with 1 and 2, without fire or smoke, and with no output failure.

d) Test result

Voltage level (V)	HWS1000-15	HWS1500-34
1	PASS	PASS
3	PASS	PASS
10	PASS	PASS

Table B.2: Test result of conducted faults test

2 & 3): Voltage dips, voltage interruptions test (IEC 61000-4-11)

a) Used equipment

Test Generator, oscilloscope.

b) Test conditions

Input voltage: 100, 230 V alternating current
Output current: 100%

Output voltage: nominal (15 V of 24 V)

Number of tests: 3

Test interval: 10 sec.

Environment temperature: 25 degrees.

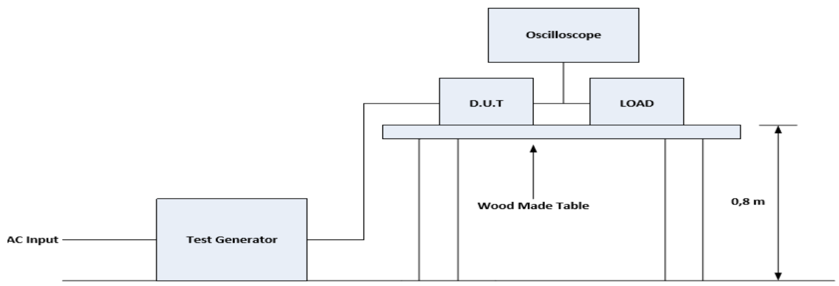

Fig. B.2: Voltage dips, short interruption, immunity test

c) Acceptable conditions

- Output voltage regulation was not more than ± 5% of the initial value, during the test.
- Output voltage should be in output voltage regulation specification after the test.
- Along with 1 en 2, without fire or smoke, and no output failure.

d) Test Result

FOR HWS1000-15

Tests Level	Dip Rate	Continue Time	HWS100015
70%	30%	500 ms	PASS
40%	60%	200 ms	PASS
0%	100%	10,20,5000 ms	PASS

Table B.3: Test result of Voltage dips, short interruption immunity test

For HWS1500-24

Tests Level	Dip Rate	Continue Time	HWS1500-34
70%	30%	10 ms	PASS
40%	60%	100 ms	PASS
0%	100%	5000 ms	PASS

Table B.4: Test result of Voltage dips, short interruption immunity

4): Overvoltage (Surge test) (IEC61000-4-5)

a) Used equipment

Surge generator, coupling impedance (common:13Ω- standard:3Ω), cooling capacity (common: 9 µF - standard:18 µF)

b) Test conditions

Input voltage: 100, 230 V alternating current

Output voltage: 100%

Output voltage: nominal (15 V or 24V)

Phase: 0^0, 90^0

Environment temperature: 25 degrees

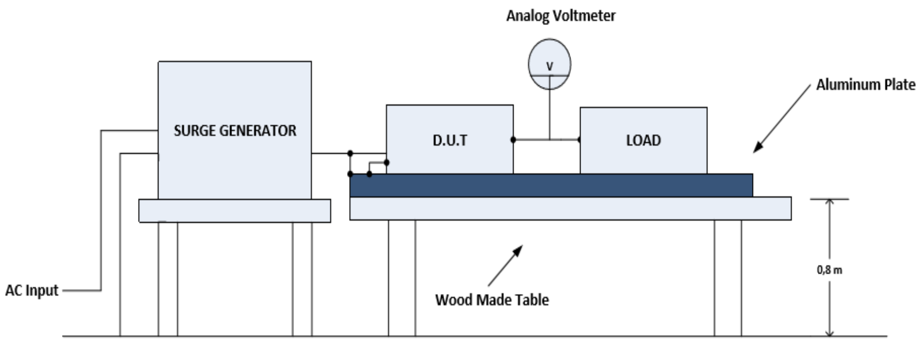

Fig. B.3: Surge Immunity Test

c) Acceptable conditions

- Output voltage regulation not more than ± 5% from the initial value (before the test) for the test.
- Output voltage should be in output voltage regulation specification after the test.
- Together with 1 and 2, no fire or smoke, and without output failure.

d) Test result

For HWS1000-15

Test Voltage (common)	HWS1000-15	Test Voltage (KV)Normal	HWS1000-15
0.5	PASS	0.5	PASS
1.0	PASS	1.0	PASS
3.0	PASS	2.0	PASS
4.0	PASS	-	-

Table B.5: Surge immunity test result Test for HWS1000-15

For HWS1500-34

Test Voltage (KV)Common	HWS1500-34	Test Voltage (KV)Normal	HWS1500-34
0.5	PASS	0.5	PASS
1.0	PASS	1.0	PASS
3.0	PASS	2.0	PASS
4.0	PASS	-	-

Table B.6: Surge immunity test result Test for HWS1500-24

5) Fast transients (Burst Immunity Test) (IEC61000-4-4)

a) Used equipment

- EFT / B Generator
- The EFT / B Generator uses electrical fast transients
- (EFT) for immunity testing in accordance with international, national standards of manufacturers, which includes the latest IEC / EN 61000-4-4 standards.

b) Test conditions

Input voltage: 100, 230 V AC

Output current: 100%

Output voltage: nominal (15 V or 24V)

Number of tests: 3

Environment temperature: 25 degrees

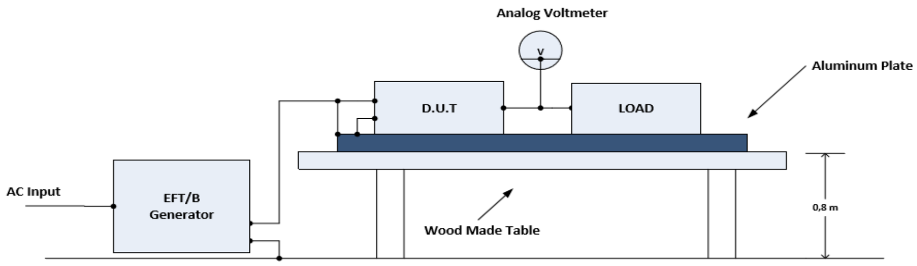

Fig. B.4: Burst Immunity Test

c) Acceptable conditions

- output voltage regulation is not more than ± 5% of initial value (before test) during test.
- Output voltage should be in output voltage regulation specification after the test
- Along with 1 and 2, no fire or smoke, nor does no output failure.

d) Test result

Test Voltage (KV)	Repetition Rate (KHZ)	HWSI000-15	HWSI500-34
0.5	5	PASS	PASS
0.1	5	PASS	PASS
0.2	5	PASS	PASS

Table B.7: Test Result Burst Immunity Test

3: Sub-conclusion on immunity

The most important part of the system, the converter which has already been tested. The other parts (for example the current regulator and the sensor) are not connected to the input voltage. So, they have no influence on this. The transducer was tested in five above-mentioned tests (according to HWS, test data). The results are within the limits of the standard. These tests do not need to be repeated.

The system satisfies the immunity standards.

Appendix C - Emission standard

1: Introduction

EM emission is the disturbance of equipment which is sensitive to it. EM disturbances can work in more than one direction. Disrupting more than one device, or multiple sources, has a cumulative effect on a single piece of equipment. For example, air traffic control radar can affect the display of a laptop computer used in an aircraft, as well as other vital devices in use on the ground. At the same time, emissions from the same laptop computer can converge with those from cell phone systems, disrupting the systems in the aircraft.

2: Emission standard

2.1: standard IEC 61000-6-4

This part of IEC 61000 for emission regulations EMC applies to electrical and electronic equipment used in industrial environments. Emission requirements in the frequency range from 0 Hz to 400 GHz are also included.

Port	Frequency range	Limits	Basic standard
1) **Enclosure port**	30 MHz-330 MHz 230MHz-000MHz	40 dB(uv/m) peak at 10 m 47 dB(uv/m) peak at 10 m	CISPR 16-2-3
3) **Low voltage AC mains port**	0,15 MHz-0,5MHz	79 dB(uv) 66 dB(uv)	CISPR 16-3-1, 7.4.1 CISPR 16-1-3, 4.3
	0,5MHz-30MHz	73 dB(uv) 60 dB(uv)average	
3) **Telecoms. /Network port**	0,15 MHz-0,5MHz	97 dB(uv)- 87 dB(uv)Quasi-peak 84 dB(uv)- 74 dB(uv) average 53 dB(uA)- 43 dB(uA)Quasi-peak 40dB(uA) 30 dB(uA) average	CISPR 22
	0,5MHz-30MHz	87 dB(uv) peak 74dB(uv)average 43 dB(uA) peak 30dB(uA)average	

Table C.1: Maximum emission limits

2.2: Limits

Table 3.3 shows the maximum emission limits according to the IEC61000-6-4 for 3 ports.

1) Enclosure port
2) Low voltage AC port
3) Telecommunication/network port

Enclosure port

This refers to the EM radiation which radiates through the housing of the device. Since this is a grounded metal case, it is expected that this EM radiation (> 30MHz) always falls within the norm.

Low voltage AC port

This refers to the EM radiation through the power cable. This certainly applies, because a power cable is used. Test results are available for the TDK-HWS voltage converters.

- **Limit values for frequency 0.15-0.5 MHz**

Norm: Norm CISPR 16-2-1
Limit value quasi peak: 79 dB (uV)
Limit value average: 66 dB (uV)

- **Limit values for frequency 0.5-30 MHz**

Norm: Norm CISPR 16-1-2
Limit value quasi peak: 73 dB (uV)
Limit value average: 60 dB (uV)

- **Telecommunication/network port**

This applies to EM radiation on the Ethernet port of this system. Since this is a standardized Ethernet controller, which is controlled with standard software and because a shielded cable is also used, it is expected that the EM radiation will always fall within the standard.

2.3: Measurement method

- **Measurement of disturbances conducted along cables**

When testing for compliance with emission limits for electromagnetic disturbances conducted along cables, some items will be considered minimum. There are two methods of measuring conducted disturbances, either as voltage or as current. Both methods can be used to measure the three types of conducted disturbances. They are: the common mode voltage, the common mode current and the asymmetric mode voltage. The type of measuring equipment is chosen to determine the fault characteristics (voltage and current probe).

- **Requirements of probes**

The probe must make contact with the capacitor to prevent the measuring receiver from being damaged by the line voltage. To make a particular interference measurement, the voltage probe must make contact with a particular resistor (for example, 50 ohms). The voltage probe must indicate a special point. The reference ground must be connected to this point by a cable of maximum length, unless the reference ground is connected to the DUT in a special way.

- **The requirements of the flow probes**

low Probes make possible measurement of the three types of flow disturbances on the power supply cables, signal cables, cables, load, etc. A clip-on assembly of the probe will facilitate its use. In any given frequency range, the insertion loss caused by the current probe must be less than 1 Ω. The current probe is constructed in such a way that the influence of electric fields on the measurement results can be neglected.

- **Test equipment configuration**

In order to measure the fault voltage, the equipment for the test (DUT) is connected to the power supply and to any other external network via one or more artificial networks. See the following Figure:

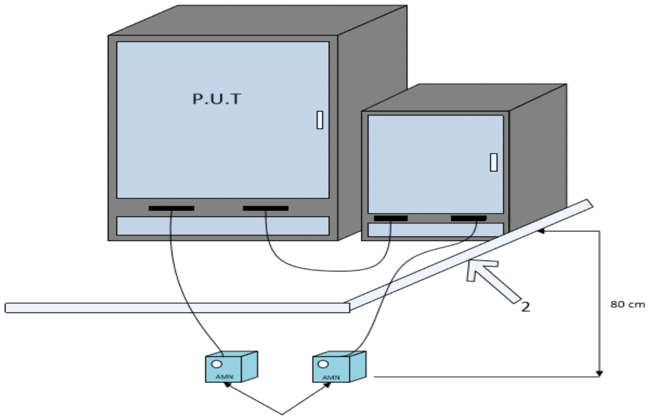

Fig. C.1: Test equipment configuration

3.4: Test result

- **For HWS1000-15 [17]**

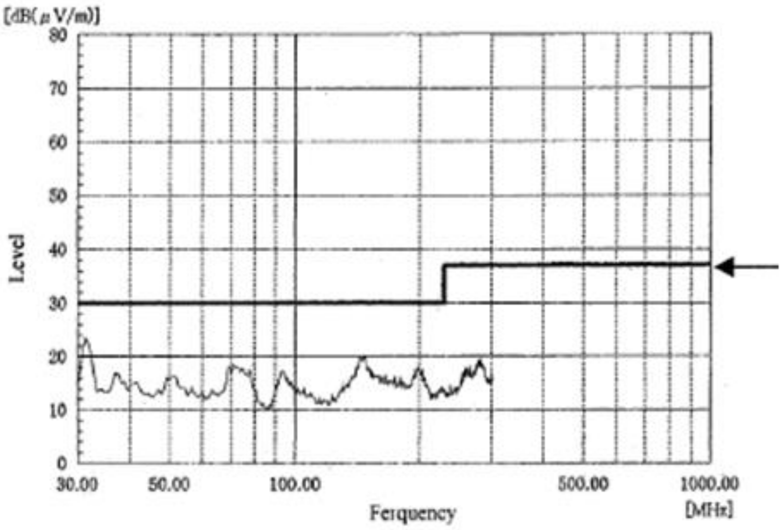

Fig. C.2: Electric magnetic interference properties for HWS 1000-15

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[17] **WS1000- Evaluation Data-2008**

- **For HWS1500-24 [18]**

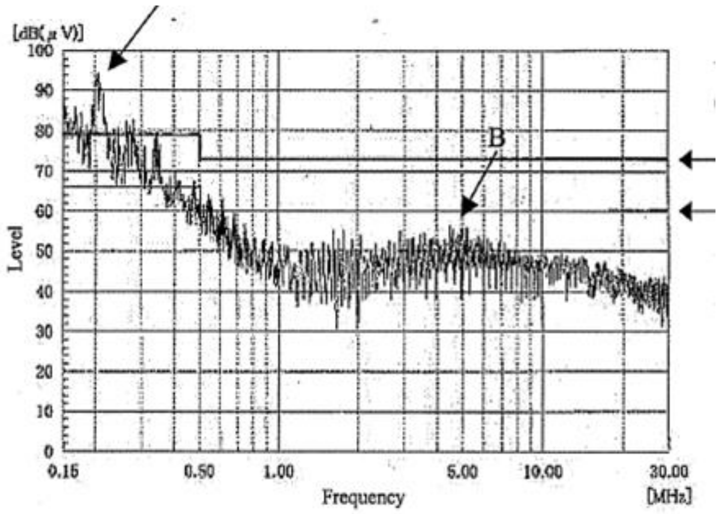

Fig. C.3: Electric magnetic interference properties For HWS 1500-24

3: Sub-conclusion Emission

In order to test the emission from the Low Voltage port, certain devices should be available, such as a frequency meter (equalizer). According to the rectifiers that supply these special devices, the emission test passes.

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[18] **HWS1500- Evaluation Data-2008**

Appendix D- Harmonic standard

1: Introduction

An electrical system supplies power to loads by supplying current at the fundamental frequency. Fundamental frequency current can only deliver real current. Current delivered at harmonic frequencies which cannot deliver real power to the load. Power systems are designed to operate at a frequency of 50 or 60 Hz. However, certain types of charges produce currents and voltages with frequencies that are multiples of the 50 or 60 Hz fundamental frequency. These higher frequencies are known as power system harmonic.

2: Harmonic Standard

IEC 61000-3-2 deals with the limitation of the harmonic currents injected into the public grid system. It specifies limits of harmonic components of the input current which can be produced by equipment that has been tested under specified conditions. It applies to electrical and electronic equipment with an input current of up to 16 A per phase and intended for connection to public low-voltage distribution network systems.

2.1: Limit values

There are several classes for the boundary of the harmonic. See the following figure:

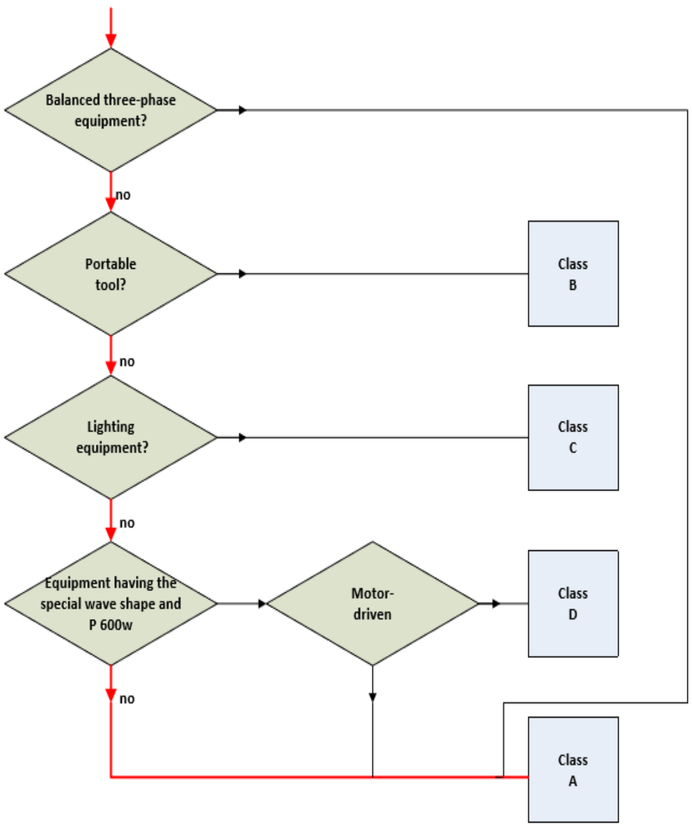


Fig.D.1: scheme for determining the class

Since the system is not connected to the public low-voltage grid, this standard does not strictly apply. If the low-voltage grid could be connected to it later, this standard does apply. According to the flow chart, class A would apply. In the standards for appliances, requirements are set for the harmonic currents which may be present in the current drawn from an appliance. Table 3.9 gives an example of the maximum harmonic currents in a device up to and including a nominal current of 16 A.

Harmonic n	Maximum harmonic current
Odd harmonic	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
15<n<39(n=ood)	0.15*(15/n)
Even harmonic	
2	1.08
4	0.43
6	0.30
8<n<40(n=even)	0.23*(8/n)

Table D.1: Maximum harmonic currents 16A

3.3: Measuring Method

For Class A equipment, the harmonic of the input current does not exceed the values in Table E.1. The harmonic of the input current for some equipment does not exceed the values in Table 1 multiplied by a factor of 1.5. The harmonic currents of the equipment under test (DUT) are measured according to the circuits in Fig. E.2 for three phase equipment. [6]

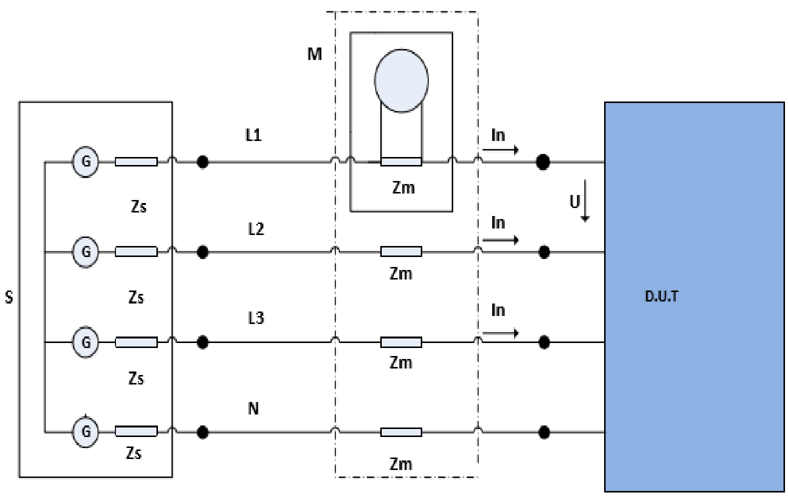


Fig.D.2: Measurement method of the harmonic currents of the test equipment (DUT0)

Where means:

S: power source

M: measuring equipment

DUT: test equipment

G: open line voltage from the power source

Zm: input impedance of the measuring equipment

Zs: internal impedance selection of the power source

In: harmonic component of the order of the power line

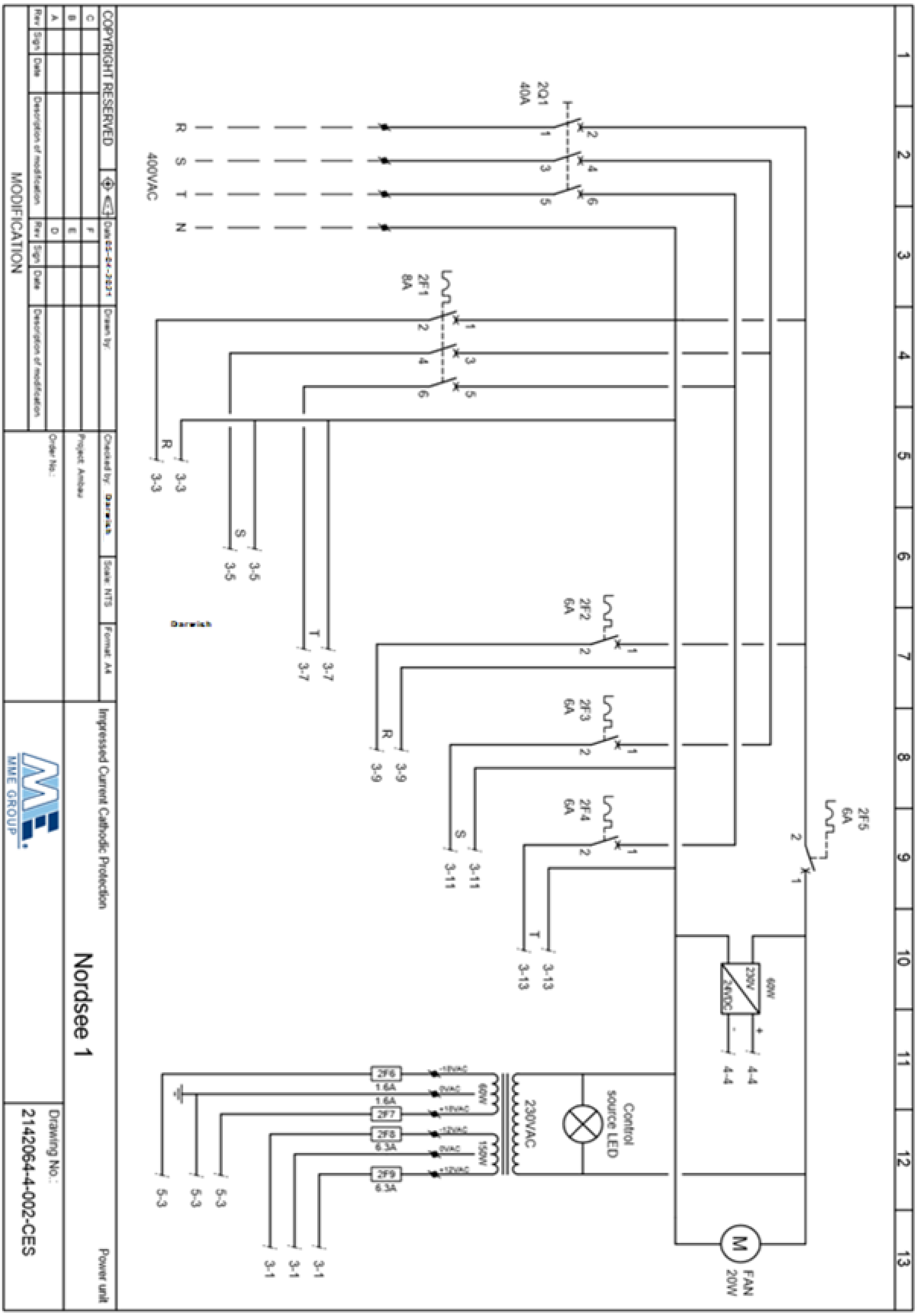
U: test voltage (as an example between stages L1 and L2)

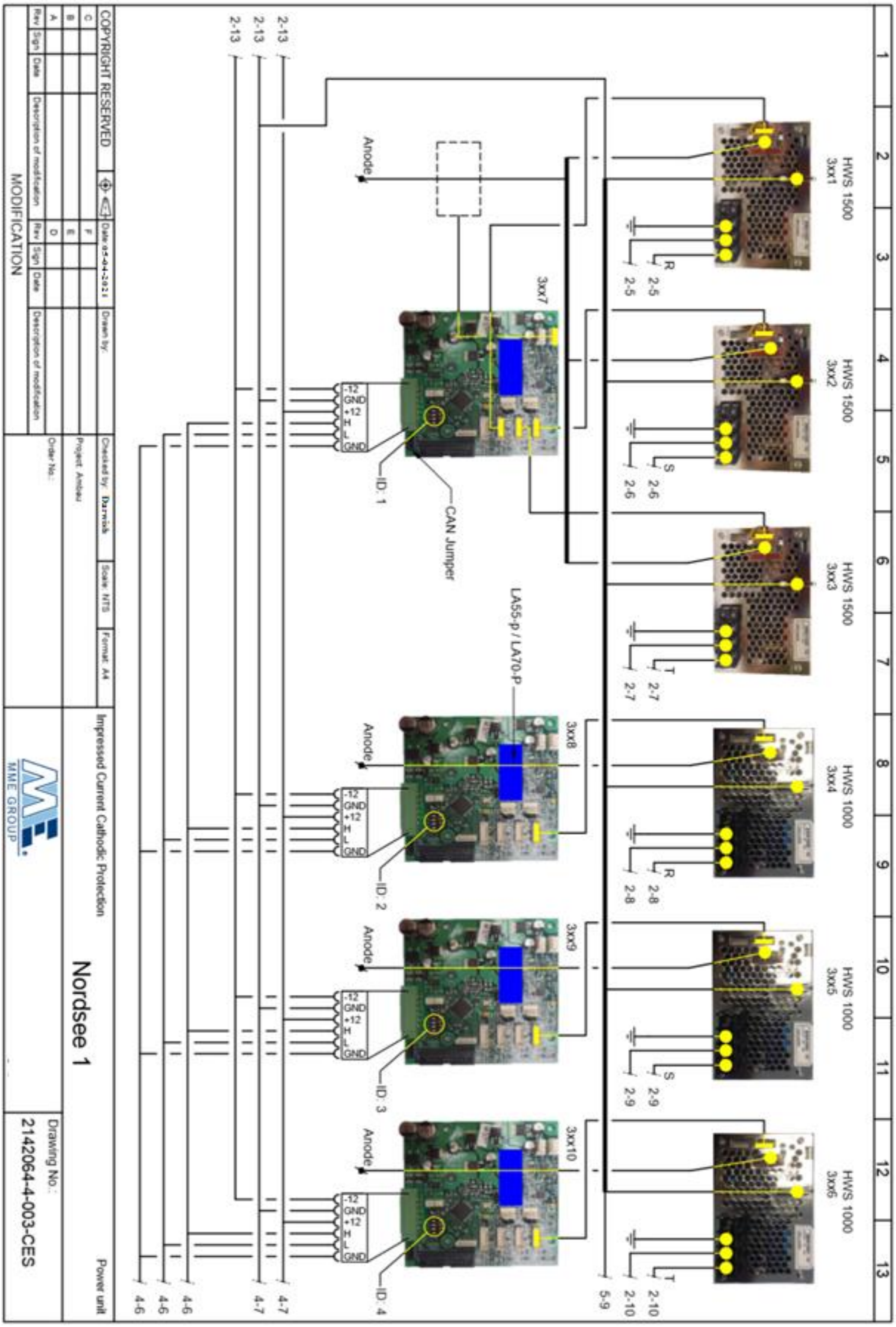
For certain types of equipment, such as single-phase uncontrolled rectifiers or the harmonic amplitudes, the supply voltage widely varies. In order to minimize variability, it is recommended to maintain the voltage at the connection point of the measuring equipment to 230 V or 400 V within ± 1.0 V, evaluated against the same 200 ms viewing window used for a harmonic assessment.

3: Sub-conclusion Harmonic

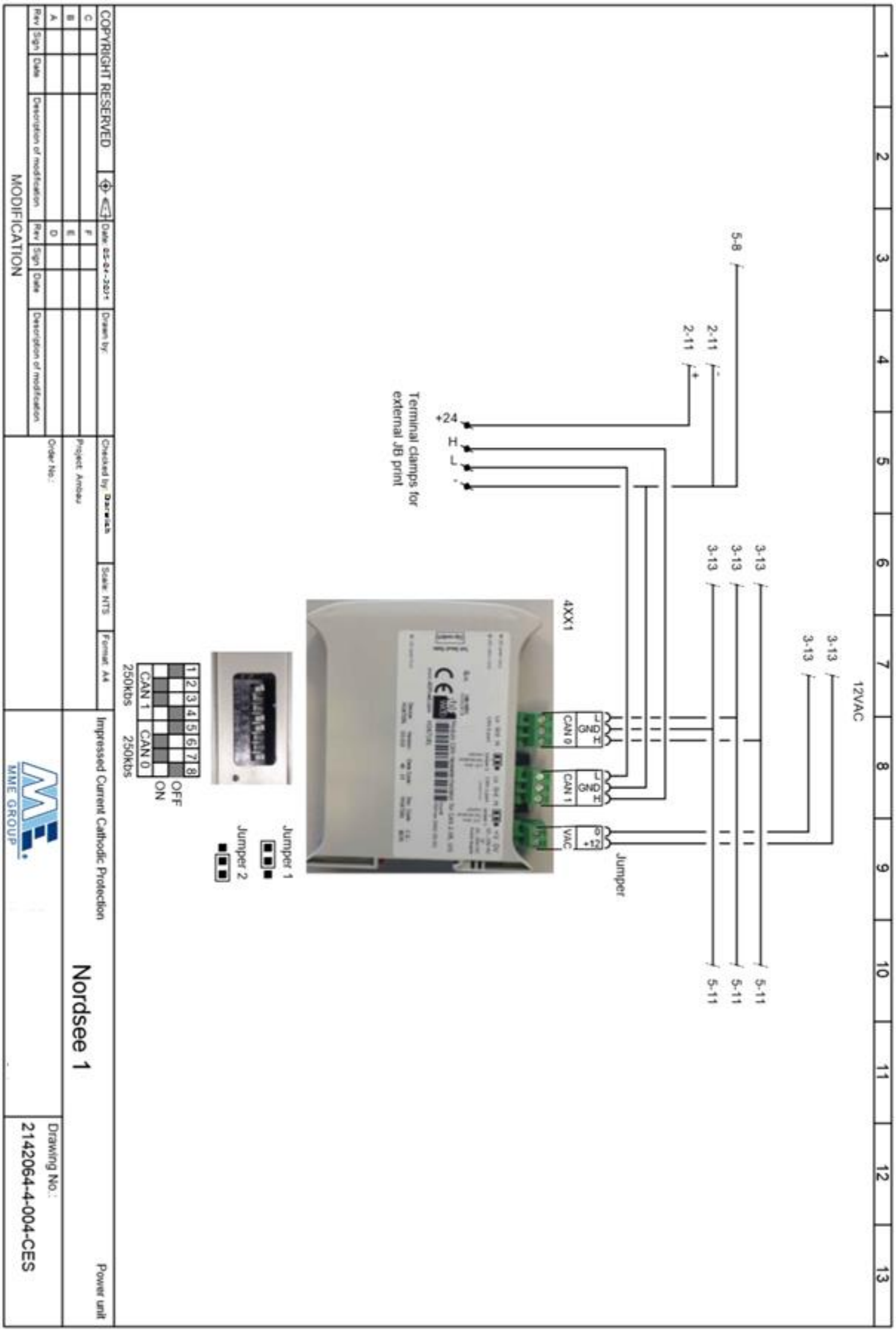
The results of the harmonics and the data of standard ICE61000-3-2 are compared with each other in chapter 5.

Appendix E-Electrical schematic





HWS 1500 3xx1
HWS 1500 3xx2
HWS 1500 3xx3
HWS 1000 3xx4
HWS 1000 3xx5
HWS 1000 3xx6
3xx7
3xx8
3xx9
3xx10
Anode
CAN Jumper
LA55-p / LA70-P
ID: 1
ID: 2
ID: 3
ID: 4
-12
GND
+12
H
L
GND
COPYRIGHT RESERVED
MODIFICATION
Impressed Current Cathodic Protection
Nordsee 1
Power unit
Drawing No.:
2142064-4-003-CES
MME GROUP
Scale: NTS
Format: A4


12VAC
5-8
2-11
2-11
3-13
3-13
3-13
3-13
3-13
5-11
5-11
5-11
4XX1
Jumper
Terminal clamps for external JB print
+24
H
L
CAN 0
CAN 1
L
GND
H
VAC
0
+12
Jumper 1
Jumper 2
1 2 3 4 5 6 7 8
CAN 1
CAN 0
250kbs
250kbs
OFF
ON
COPYRIGHT RESERVED
Rev
Sign
Date
Description of modification
MODIFICATION
Drawn by:
Checked by:
Scale: NTS
Format: A4
Order No.:
Impressed Current Cathodic Protection
Nordsee 1
Power unit
MME GROUP
Drawing No.:
2142064-4-004-CES

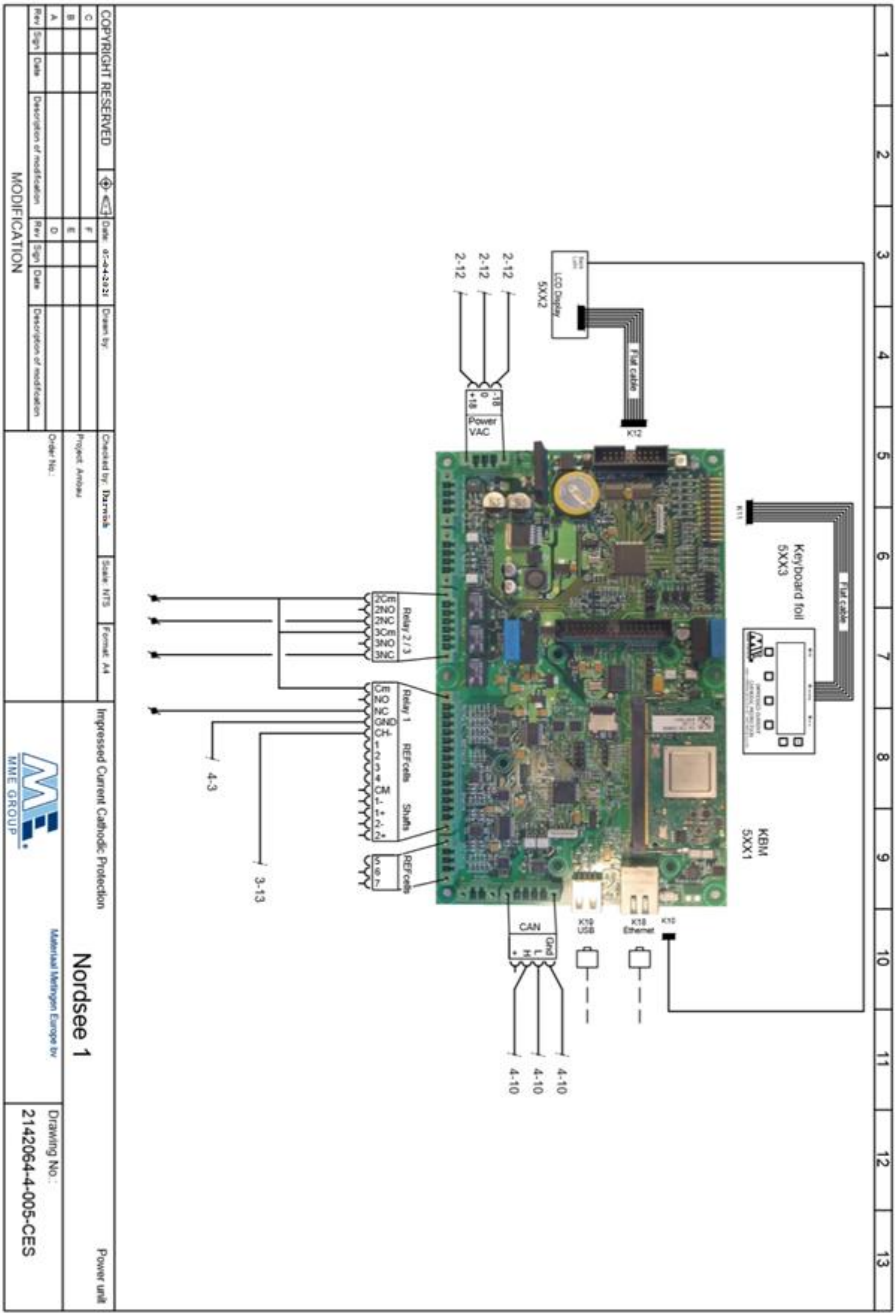


Fig. E.1: Electrical Schematic

Appendix F – Results and graphs of test 1

1: Introduction

In this first test, the measurements are made of, among other things, the efficiencies, the power factor, the current and voltage harmonics, the output current and output voltage.
The measurement setup is assessed on the basis of the results of this first test and the measurement results are verified. After this, possible optimization steps would follow.

2: Expectation

The power P_{phase} of one phase is:

$$P_{phase} = V_{phase} I_{phase} cos\emptyset \dots (F.1)$$

For the three phases together:

$$P_{in} = V_{phase} I_{phase} \dots (F.2)$$

The relationship between the shunt current (Iout) and the AC supply current (I_{phase}) is given by:

$$\eta = \frac{V_{out} I_{out}}{V_{phase} I_{phase}\ cos\emptyset} \dots (F.3)$$

Then is:

$$V_{phase} I_{phase} cos\emptyset\ \eta = V_{out} I_{out} \dots (F.4)$$

The input voltage is 230 V. To determine the efficiency:

$$I_{phase} cos\emptyset\ C = P_{out} \dots (F.5)$$

If Pout increases, $(I_{phase} cos\emptyset)$ must also increase by equal V_{out}, where is constant. In this state, the result becomes one curve, because the relationship between V_{out} and I_{phase} (or $cos\emptyset$) is Constant, which is:

$$\frac{P_{out}}{I_{phase}\ (or\ cos\emptyset)} \dots . (F.6)$$

As Iout increases, the factor (I_{phase} $(or\ cos\emptyset)$)also increases at a fixed Vout. In this state, the result becomes more than one curve, because the relationship between and depends on the different values of the output voltage, which is:

$$\frac{I_{out}}{I_{phase}\ (or\ cos\emptyset)} = \frac{constant}{V_{out}} \dots . (F.7)$$

If Vout rises, I_{phase} $(or\ cos\emptyset)$ should be also rise at a set Iout. In this state, the result becomes more than one curve, because the relationship between V_{out} and I_{phase} (or $cos\emptyset$) depends on the different values of the output voltage, which is:

3: Block diagram

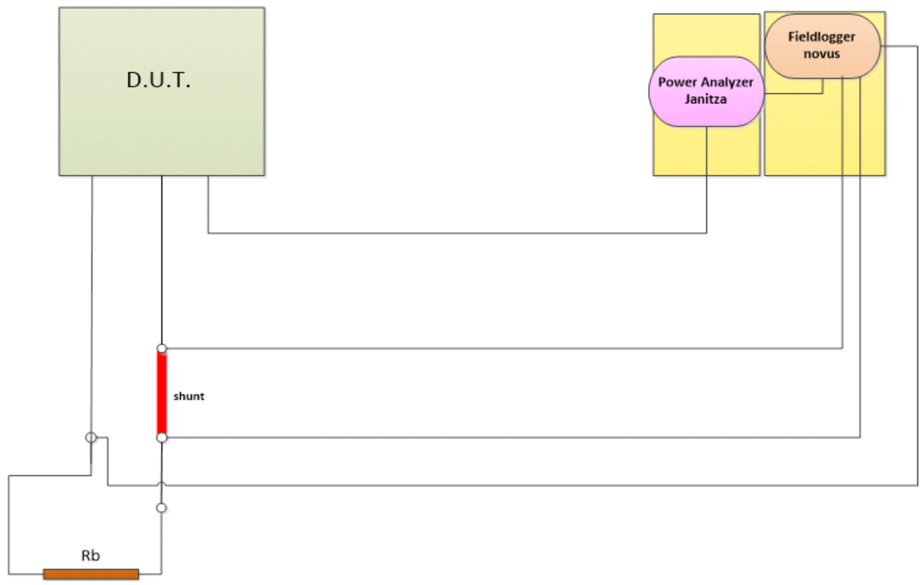


Fig. F.1: Block diagram of the tests

4: The purpose of the test

The relationship between output current (Iout) and output voltage (Vout) versus efficiency (η) should be tested for the different loads (Rb).

5: measurement equipment

Cabinet 1: Device under test (DUT)

- 3xTDK-HWS-15V-1500 (15V, 100A)
- 1xcurrent -controller (DCM-module)

Cabinet 2: measurement Devices

- Power analyser (UMG 604- Janitza)
- FieldLogger (Novus).

Cabinet 3: Control and process system

- AC supply (AE Europe, prim. 230V/sec. 2x12v)
- Mother board (KBM)
- Network (Colibri)

Cabinet 4: Variable load.

Other devices

- Clamp Meter
- Voltmeter

6: Measuring

Entrance

- I: L_1-L_2/ L_2-L_3/ L_3-L_2
- V: L_1-L_2/ L_2-L_3/ L_3-L_2
- Cos phi
- Input Power

Output

- I: I_{out}
- V: V_{out}

7: The modbus address

The Modbus address can be found in the UMG 604 brochure.

	Address	Explanation	Unit	
I_{in}	19012, 19014, 19016	Current L_{1-N}, Current L_{1-N}, Current L_{1-N}	A	
Vin, fase-fase	19006, 19008, 19010	Voltage L_1-L_2, Voltage L_2-L_3, Voltage L_3-L_1	V	
Pf	1309, 1311, 1313	Cos phi_ L_1, Cos phi_ L_2, Cos phi_ L_3	-	
P_{in}	19020, 19022, 19024, 19026	Real power L_{1-N}, Real power L_{2-N}, Real power L_{3-N}, $P_{sum} = P_1+P_2+P_3$	W	
Iout	Shunt	DC- output current	A	Measured by FieldLogger
Vout	Direct	DC- output voltage	V	Measured by FieldLogger

Table F.1: The values from the modbus address of test 1

8: The results

See data from Appendix F – Results and graphs of test 1.

9: The charts

9.1: The graph of output current versus Cos phi

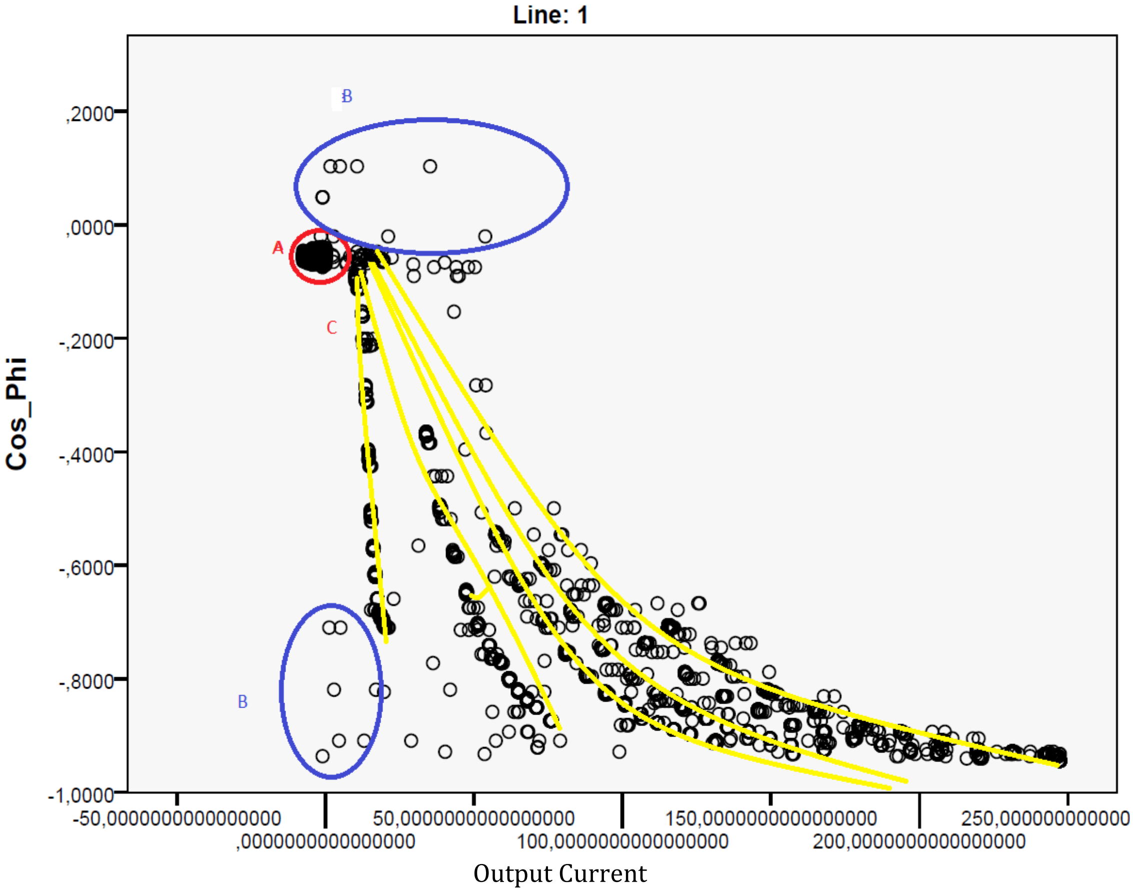


Fig. F.2: Output Current versus Cos phi

Observation measurement 1:

1. There are several values of shunt current that are negative. see A.
2. There are inaccurate values. see B.
3. There are more lines than expected. 6 lines are expected (6 loads). see C.
4. At the points it is not really clear to which line they belong.
5. The graph in this form does not provide information for calculating the output power limitation.

9.2: The graph of output voltage versus Cos phi

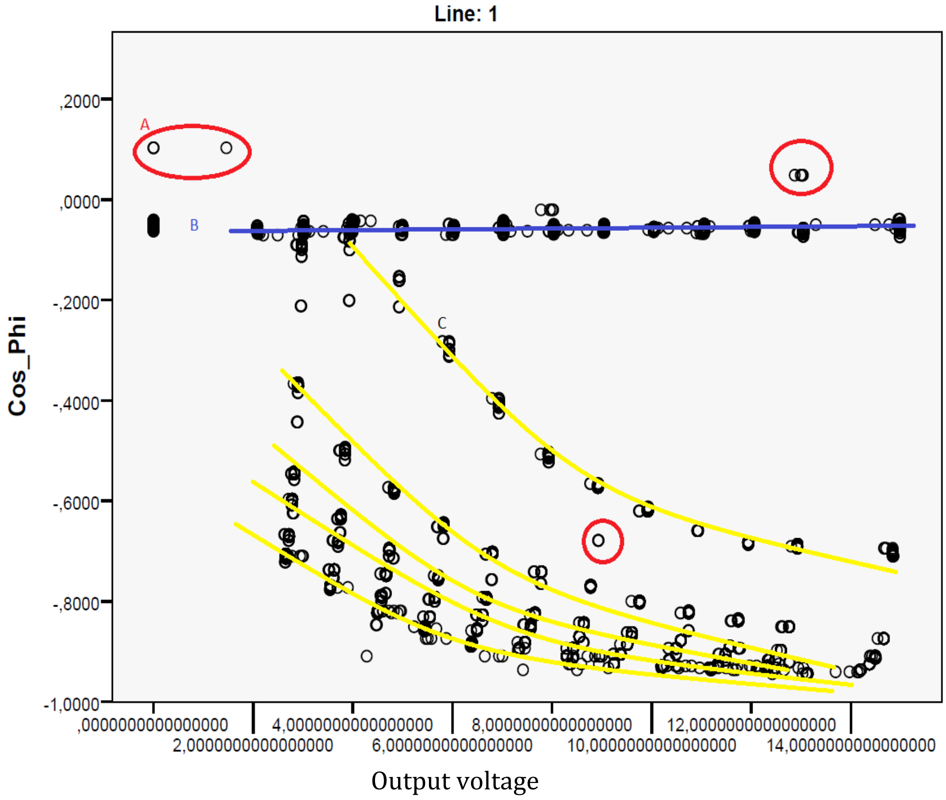


Fig. F.3: Output voltage versus Cos phi

Observation measurement 2:

1. There are small inaccurate values. See A.
2. There is an unexpected line. See B.
3. There are more lines than expected. 6 lines are expected (6 loads). See C.
4. At the points it is not really clear to which line they belong.
5. The graph in this form does not provide information for the calculation the output power limitation.

9.3: The graph of output power versus Cos phi

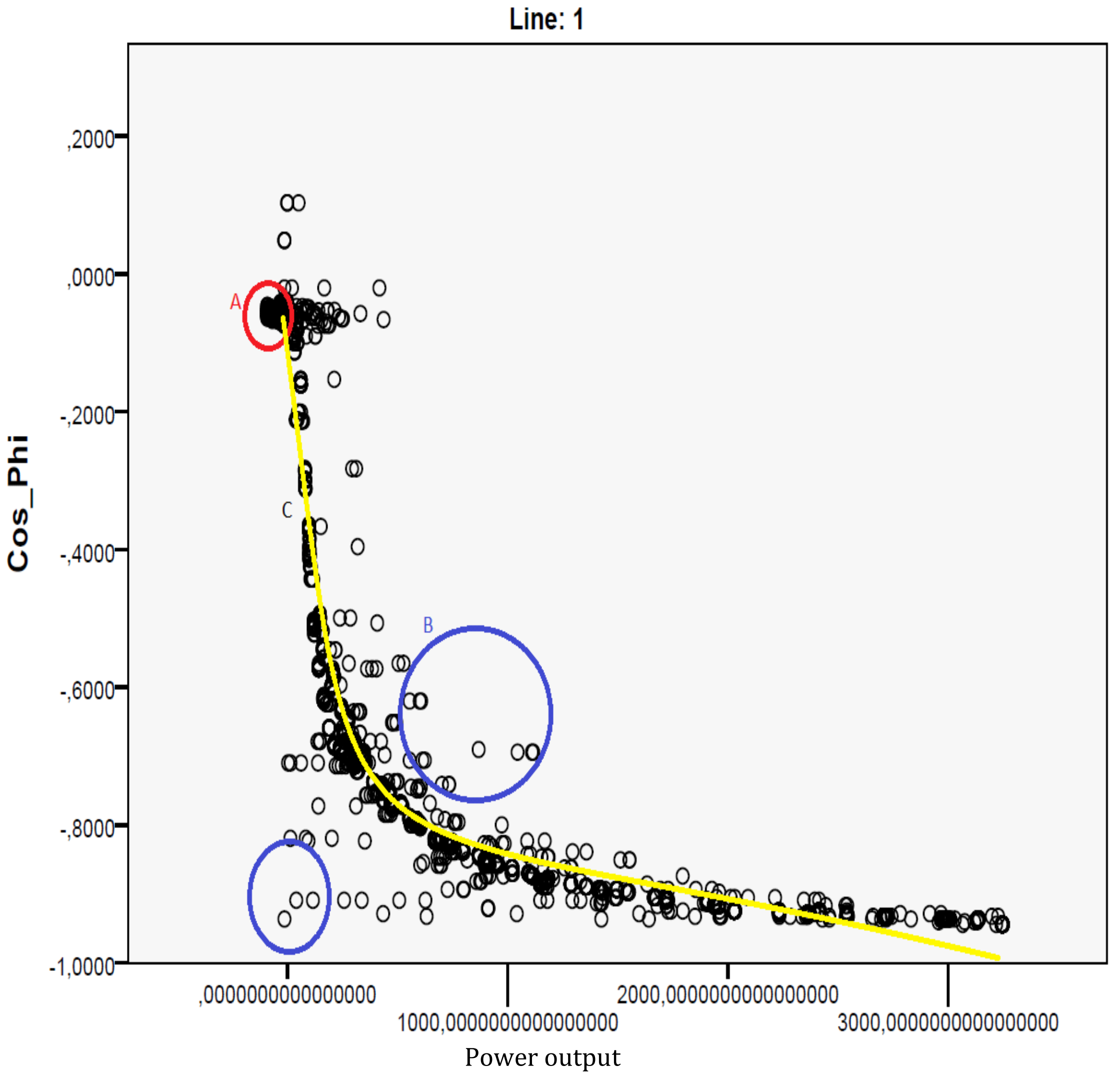


Fig. F.4: Power output versus Cos phi

Observation measurement 3:

1. There are several values of output power that are negative. See A
2. There are inaccurate values. See B.
3. Contrary to expectations, there is one line. 6 lines are expected (6 loads).
4. At the points it is not really clear to which line they belong.
5. The graph in this form does not provide information for calculating the output power limitation.

9.4: The graph of output current vs. input current

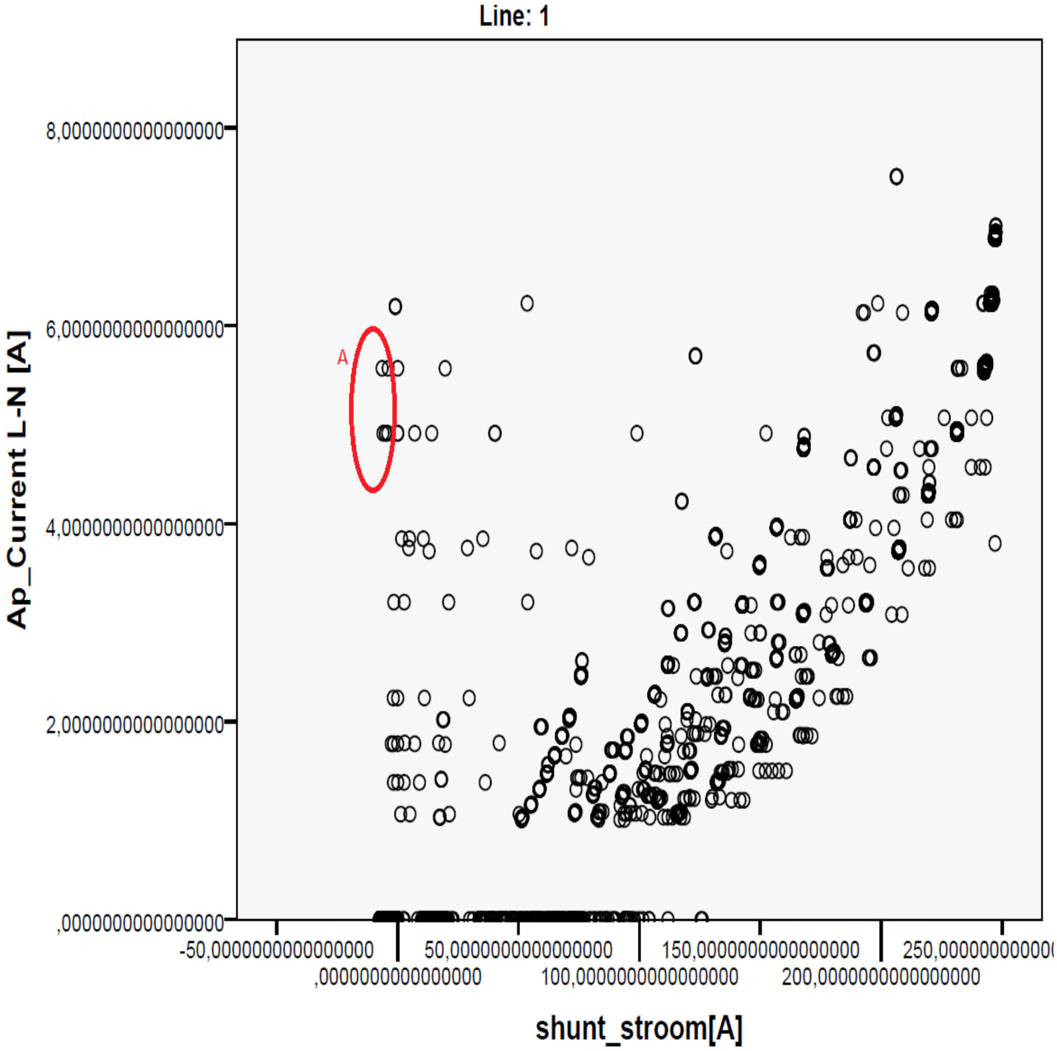


Fig. F.5: Output Current vs Input Current

Observation measurement 4:

1. There are various values of shunt current that are negative. See A.
2. The points are not clear; the curves are different than expected.
3. The graph in this form does not provide information for the calculation the output power limitation.
4. The graph in this form does not provide more information than the If vs Puit graph.

9.5: The graph of output voltage vs input current

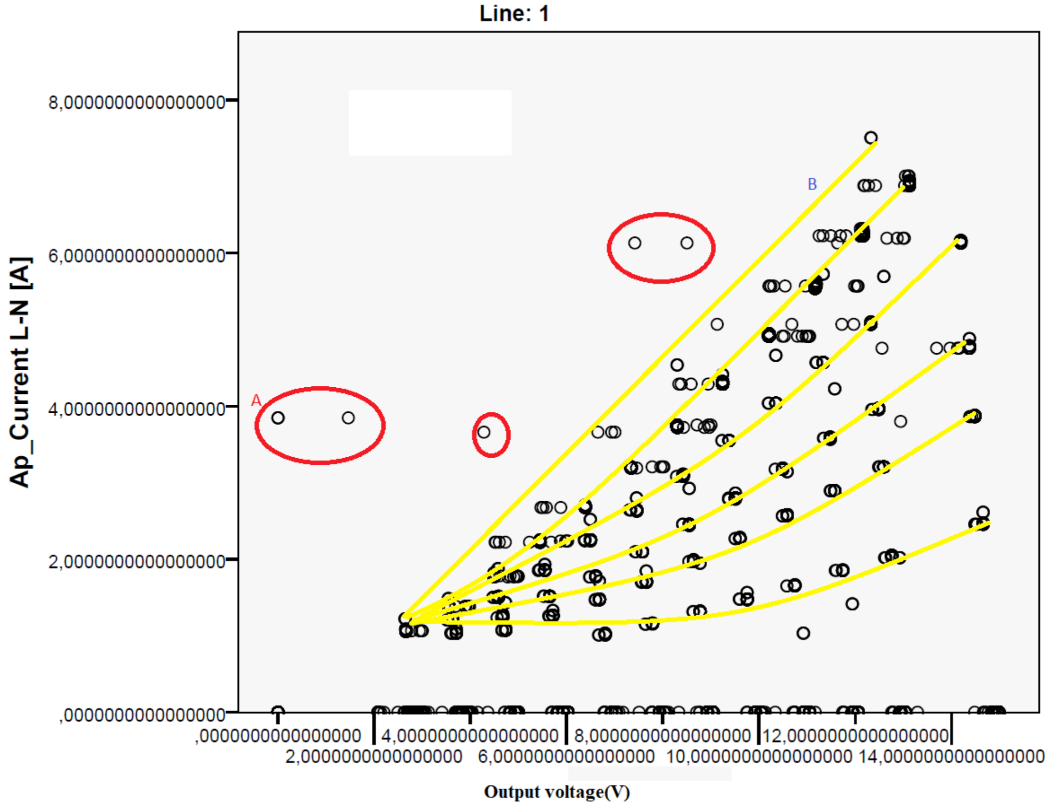


Fig. F.6: Output voltage versus input current

Observation measurement 5:

1. There are inaccurate values. See A.
2. Contrary to expectations, there is one line. 6 lines are expected (6 loads). See B.
3. At the points it is not really clear to which line they belong.

9.6: The graph of output versus input current

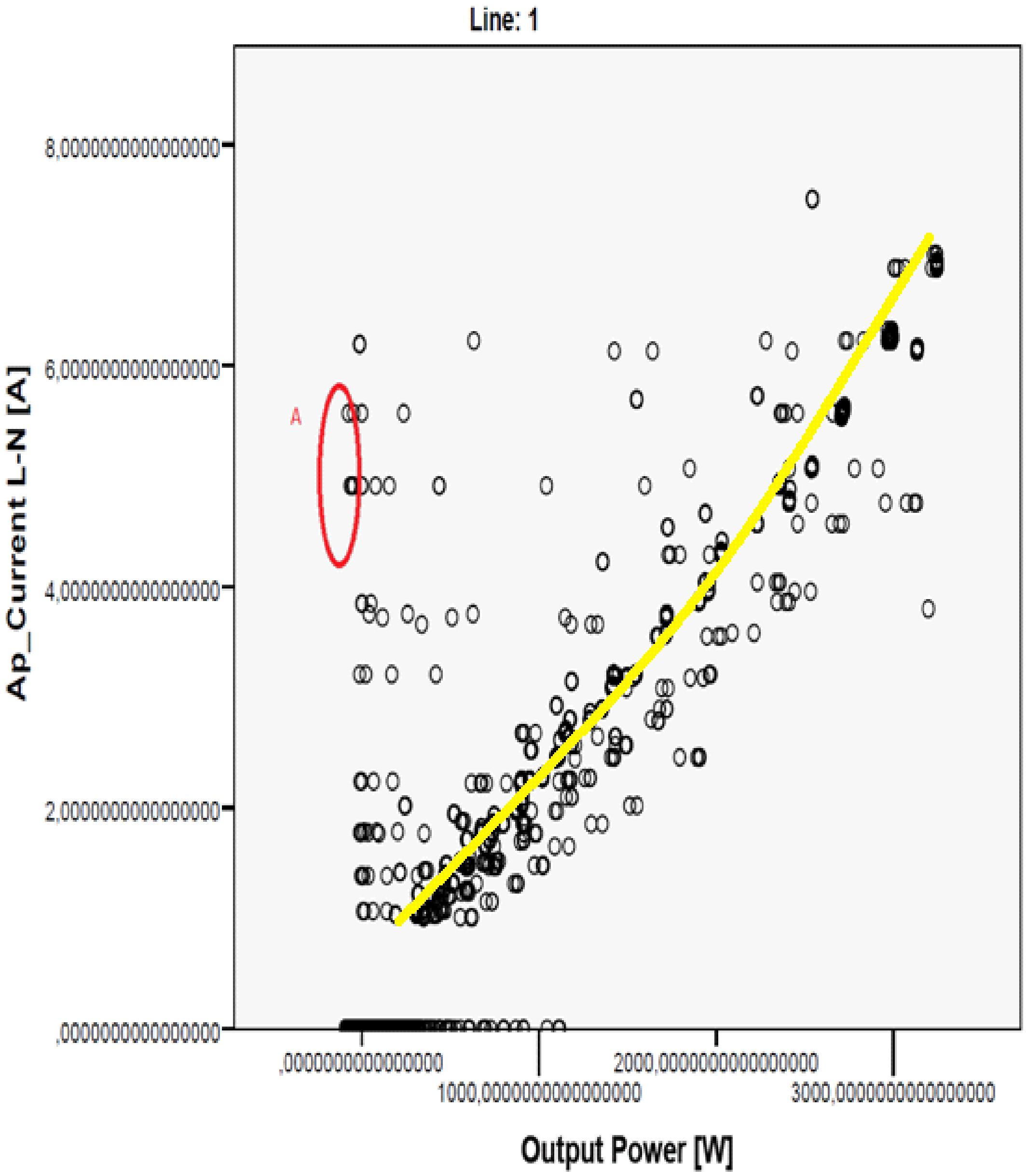


Fig. F.7: Output Power vs Input Current

1. Measurement observation 6:
2. There are several output powers values that are negative. See A.
3. The points are not clear; the curves are different than expected.

10: Recommendations

The software is programmed according to 1 measurement with 1 result per second via the FieldLogger. The variable load is programmed by PLC Mitsubishi Alpha 2, i.e., a different value of load per period. The results of the first measurements are generally reasonable and as expected, but some values are not accurate enough. There are several causes:

Recommendation 1:

Between two values of the variable load, the time which is taken for the changed results in an inaccurate measurement. After the transient, the measurement becomes accurate. So, using a manual load change, but that is not convenient. Or program the variable loads by PLC and stop the measurement during any transient time. See the following fig.

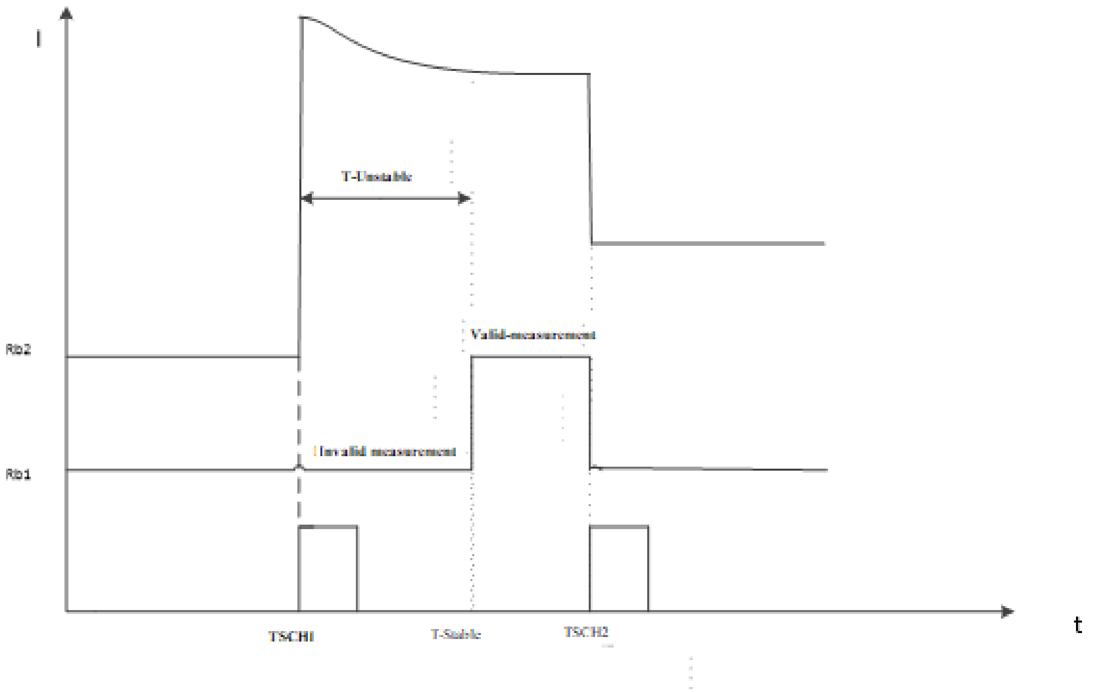


Fig. F.8: The variable load measurement

Recommendation 2:

Zero-point Current calibration.

Recommendation 3:

For control measurement, measure both sides of the clamp meter.

Recommendation 4:

During the measurement, the value of the output voltage is not accurate, namely the voltage between the positive terminal and the negative terminal does not appear to be equal to the load voltage. So, measure as close to the TDK-HWS as possible, because the long cable between TDK-HWS and the variable load gives more voltage drop.

Recommendation 5:

Adjust the measurement expectation.

Recommendation 6:

Use another data logger. (More channels).

Recommendation 7:

Drop the charts Puit vs Cos phi, Vout vs Cosϕ, Iout vs If, Vout vs If.

Recommendation 8:

Add Tension Lines in If VS Puit.

Recommendation 9:

Adding the graph of the return (η vs Puit).

Recommendation 10:

There are three main graphs for calculating the input power limitation: If vs Pout, Cosϕ vs Pout, η vs Pout.

11: Conclusions

Several conclusions can be drawn:

Conclusion 1:

The measurement can be improved: program the variable loads by PLC and stop the measurement during any transient time.

Conclusion 2:

The voltage should not be measured at the points of the variable load RB, but at the points Vout of DC-TDK-HWS power supply

12: Some results

DATE	TIME	Ap_Current	Ap_Current	Ap_Curren	Cos_P_L1	Cos_P_L2	Cos_P_L33
3/20/2015	1:45:24 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:25 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:26 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:27 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:28 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:29 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:30 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:31 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:32 PM	13.848	13.926	15.801	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:33 PM	13.848	13.926	15.801	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:34 PM	13.848	13.926	15.801	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:35 PM	13.848	13.926	15.801	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:36 PM	13.848	13.926	15.801	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:37 PM	13.848	13.926	15.801	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:38 PM	13.848	13.926	15.801	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:39 PM	13.848	13.926	15.801	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:40 PM	13.848	14.004	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:41 PM	13.848	14.004	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:42 PM	13.848	14.004	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:43 PM	13.848	14.004	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:44 PM	13.769	14.004	15.723	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:45 PM	13.769	14.004	15.723	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:46 PM	13.769	14.004	15.723	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:47 PM	13.769	14.004	15.723	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:48 PM	13.926	14.004	15.879	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:49 PM	13.926	14.004	15.879	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:50 PM	13.926	14.004	15.879	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:51 PM	13.926	14.004	15.879	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:52 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:53 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:54 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:55 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:45:56 PM	13.926	13.926	15.723	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:57 PM	13.926	13.926	15.723	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:58 PM	13.926	13.926	15.723	-0,7959	-0,8232	-0,8232
3/20/2015	1:45:59 PM	13.926	13.926	15.723	-0,7959	-0,8232	-0,8232
3/20/2015	1:46:00 PM	13.848	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:01 PM	13.848	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:02 PM	13.848	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:03 PM	13.848	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:04 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:05 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:06 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:07 PM	13.926	13.926	15.801	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:08 PM	13.848	13.926	15.879	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:09 PM	13.848	13.926	15.879	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:10 PM	13.848	13.926	15.879	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:11 PM	13.848	13.926	15.879	-0,7959	-0,8193	-0,8193
3/20/2015	1:46:12 PM	13.926	13.926	15.879	-0,792	-0,8193	-0,8193

Table F.2: The results of test 1

13: Some Graphs

- *Output voltage and output current*

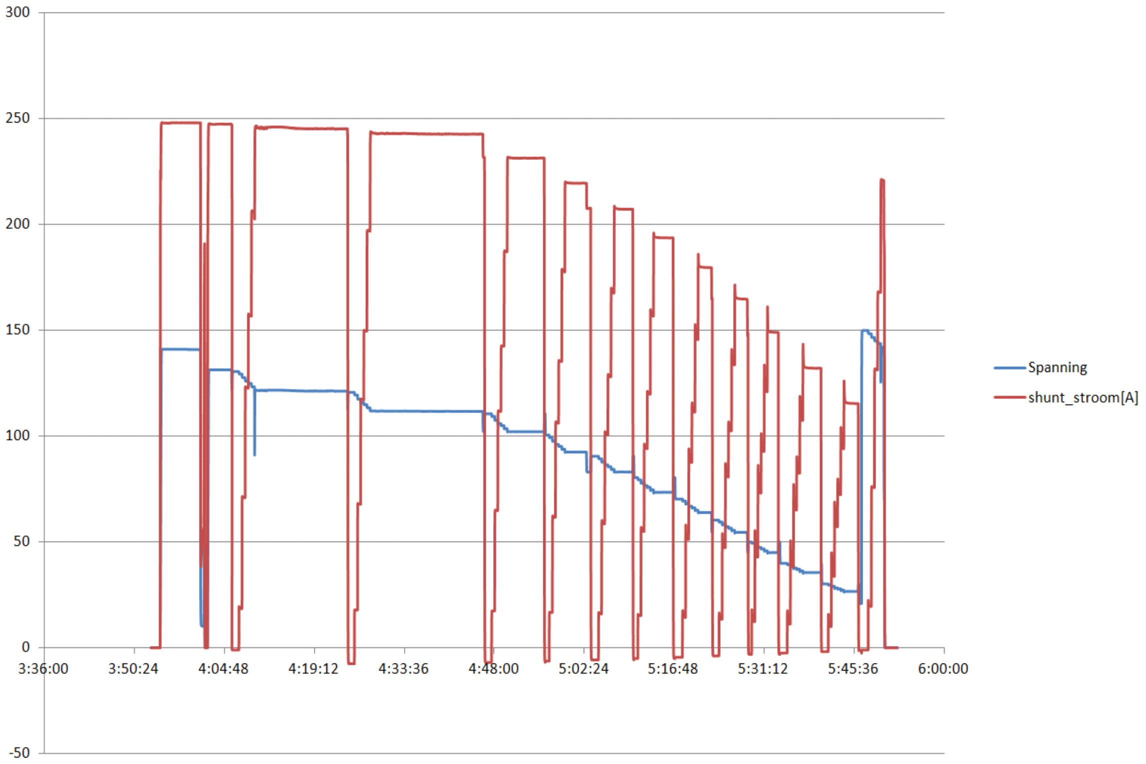


Fig. F.9: Vout vs Iout

- *Output Current versus Cos phi*

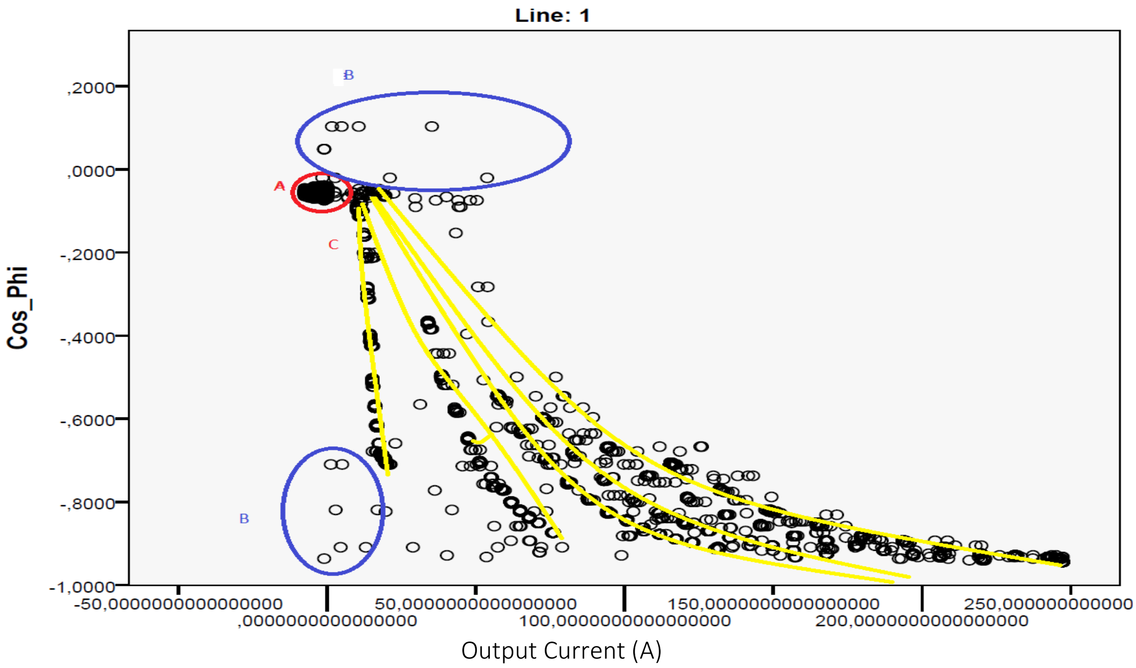


Fig. F.10: Vout vs Cos phi

Appendix G – Results and graphs of test 2

1: Introduction

In Test 2, the same measurements are taken as in Test 1, but these steps are improved by a new insight gained from Test 1. The purpose of Test 2 is to calculate the power limitation such that the input current does not exceed 16 A per phase.

After test 2, the measurement set-up is re-evaluated and it is decided whether another optimization step is needed.

2: Improvements over test 1

In test 1, certain recommendations were made. The following changes have been made:

- The unstable measurements are no longer included See Appendix F- Recommendation 1.
- The calibration of the current clamp readout has been done. See Appendix F- Recommendation 2
- Zero-point current not measured. See Appendix F- Recommendation 3.
- Measurement Voff moved. See Appendix F- Recommendation 4.
- Expectations adjusted. See Appendix F- Recommendation 5.
- Other data logger. See Appendix F- Recommendation 6.
- Three important graphs should be used as a basis for calculating the input current limitation If vs Puit, Cosϕ vs Pout, η vs Pout. See Appendix F- Recommendation 7 to 10.

3: Theoretical expectation of measurement results

There are three charts assessed, of which theoretical expectations is needed. First the general relationships are discussed, after which the expectations per graph are given graphics.

- *General Relationships Measurements*

The relationship between input power (Pin) and output power (Pout) is efficiency (η)

$$P_{out} = P_{in}\,\eta \;\ldots(G.1)$$

Whereby applies given by:

$$P_{out} = V_{out}\,I_{out} \ldots(G.2)$$

The input power is given by the following derivation; The power Pphase of one phase is:

$$P_{phase} = V_{phase} I_{phase} cos\emptyset \ldots(G.3)$$

The input voltage (U phase) and the input current (I phase) are assumed to be the same for each phase, because identical power supplies are used which will be loaded more or less identically. Then applies to the Pin for three phases together:

$$P_{in} = 3P_{phase} = 3\,V_{phase} I_{phase} cos\emptyset \ldots(G.4)$$

- *Expectation If vs Pout*

Elaboration of equation (F.4) provides:

$$I_{fase} = \frac{1}{3\,\eta\,V_{phase} cos\emptyset}\,P_{out} \ldots(G.5)$$

Since U Phase = constant, the following formula gives the expected relationship:

$$I_{fase} = f\,(\eta\,cos\emptyset\,)\,P_{out} \ldots(G.6)$$

- *Expectation Cos phi vs Pout*

Reproduce equation (G6) yields:

$$P_{out} = 3\,\eta\;V_{phase}\,I_{phase} cos\emptyset \;\;\ldots(G.7)$$

Because V_{phase} = constant, the following formula gives the expected relationship:

$$cos\emptyset = \frac{1}{3\,\eta\,V_{phase}\,I_{out}}\,P_{out} \ldots(G.8)$$

From which follows:

$$cos\emptyset\; = f\,(\eta\,,\; I_{fase}\,)P_{out} \ldots(G.9)$$

- *Expectation η vs Puit*

The expected relationship is as follows:

$$\eta = \frac{P_{out}}{P_{in}} \;...(G.10)$$

From which follows:

$$\eta \;= \frac{1}{3V_{phase}\; I_{phase} cos\emptyset}\; P_{out}\; ...(G.11)$$

Since U Phase = constant, the following formula gives the expected relationship:

$$\eta \;= f\;(\;cos\emptyset,\; I_{fase})P_{out}\; ...(G.12)$$

4: Block diagram

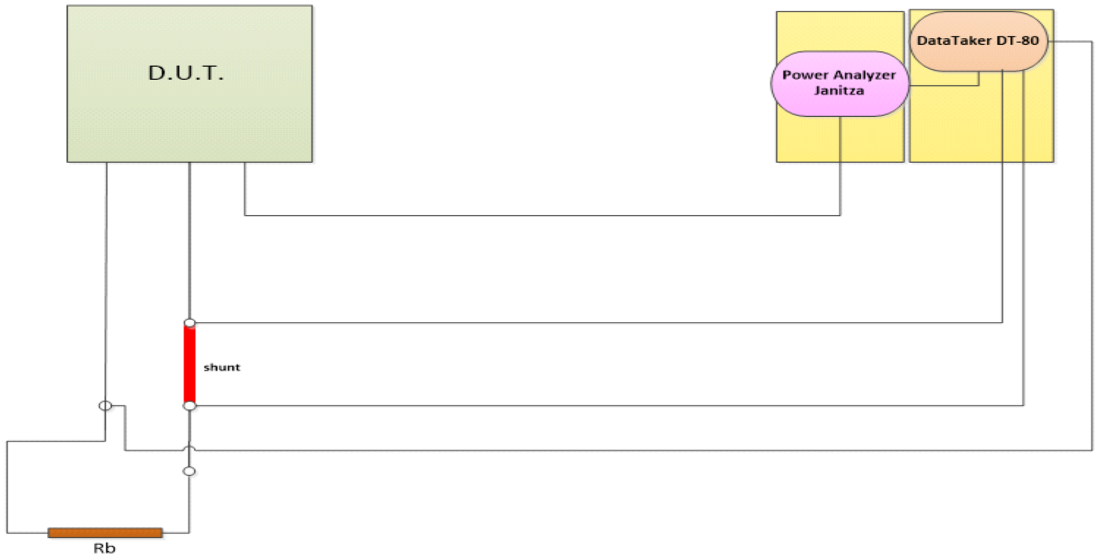


Fig. G.1: Block diagram of the tests of test 2

5: The purpose of the test

The relationship between output current (Iout) and output voltage (Vout) versus efficiency (η) must be tested for the different loads (Rb).

6: Used measuring equipment

- *Cabinet 1: Device under test (ENG)*
  - 3xTDK-HWS-15V-1500 (15V, 100A)
  - 1x power controller (DCM module)
- *Cabinet 2: measurement Devices*

Power analyser (UMG 604- Janitza)
Data taker (DT-80)

- *Cabinet 3: Control and process system*
  - AC supply (AE Europe, prim. 230V/sec. 2x12v)
  - Mother board (KBM)
  - Network (Colibri)
- *Cabinet 4: Variable load*
- *Other devices*
  - Clamp Meter
  - Voltmeter

7: measuring

- *Input:*
    - I: L_1-L_2/ L_2-L_3/ L_3-L_2
    - V: L_1-L_2/ L_2-L_3/ L_3-L_2
    - Cos phi
    - Input Power
    - Total Harmonic Distortion of Voltage (THD-V)
    - Total Harmonic Distortion of current (THD-I)
    - Voltage Harmonic (from Harmonic 1-40) for Phase 1
    - Current Harmonic (from Harmonic 1-40) for Phase 1
- *Output*
    - I: I_{out}
    - V: V_{out}

8: The modbus address

The Modbus address can be found in the UMG 604 brochure.

	Address	Explanation	Unit	
I_{in}	19012, 19014, 19016	Current L_{1-N}, Current L_{1-N}, Current L_{1-N}	A	
V_{in}, fase-fase	19006, 19008, 19010	Voltage L_1-L_2, Voltage L_2-L_3, Voltage L_3-L_1	V	
Cos phi	1309, 1311, 1313	Cos phi L_1, Cos phi L_2, Cos phi L_3	-	
P_{in}	19020, 19022, 19024, 19026	Real power L_{1-N}, Real power L_{2-N}, Real power L_{3-N}, $P_{sum} = P_1 + P_2 + P_3$	W	
I_{uit}	Shunt	DC- output current	A	Measured by Data taker
V_{uit}	Direct	DC- output current	V	Measured by Data taker
THD-V	19110 19112 19114	THD-V for phase 1 THD-V for fase 2 voor phase 2 THD-V for voor phase 3	V	
THD-I	19116 19118 19120	THD-I for phase 1 THD-I for phase 2 THD-I for phase 3	A	
Harmonic-U	13 15 17 19 ...	Harmonic 1 for phase 1 Harmonic 2 for phase 1 Harmonic 3 for phase 1 Harmonic 4 for phase 1 Etc. till Harmonic 40	V	
Harmonic-I	333 335 337 339 ...	Harmonic 1 for phase 1 Harmonic 2 for phase 1 Harmonic 3 for phase 1 Harmonic 4 for phase 1 Etc. till Harmonic 40	A	

Table G.1: The values from the modbus address of test 2

9: The results and the graphs

See data in Appendix G – Test 2 Results and Graphs.

9.1: The output power vs the input current

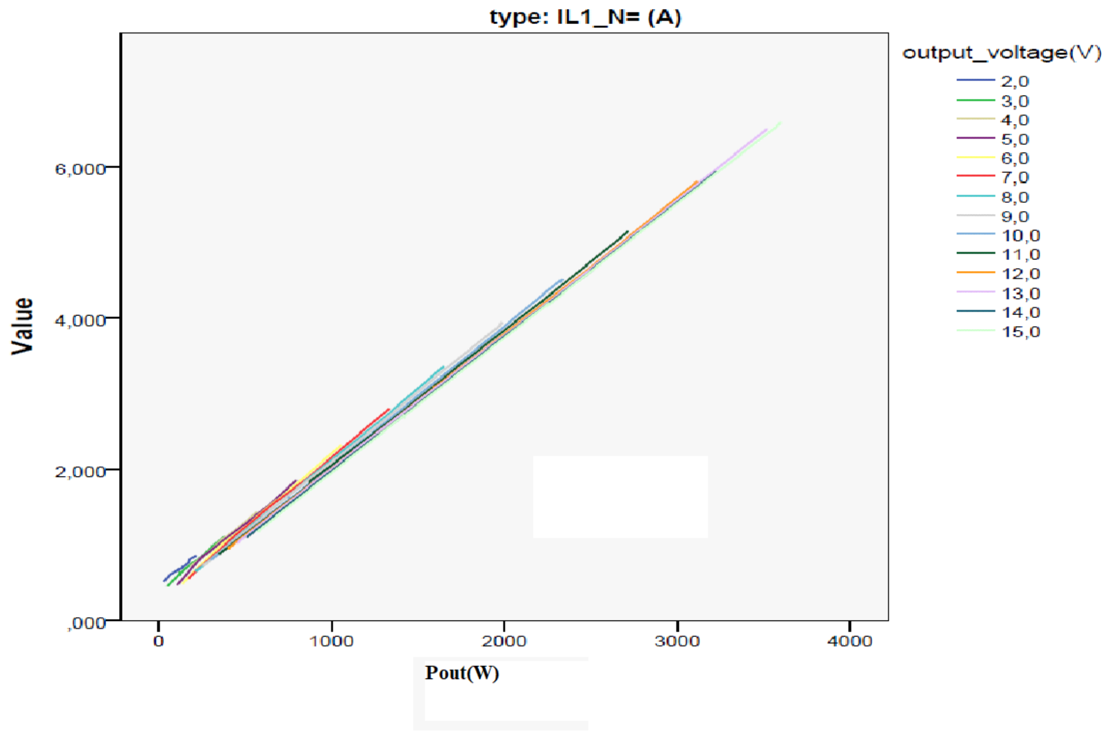


Fig. G.2: The output power vs the input current

Observation measurement 1:

1. The results contain no more noise.
2. The relationship between the output power and the input current is approximately linear.
3. This graph can be used to calculate the input current at a given output current.
4. The maximum output power is not reached.
5. The slope of the output power and input power (at a given output voltage, the efficiency inversion is $\frac{1}{\eta}$

9.2: The relationship between the power output and Cos phi

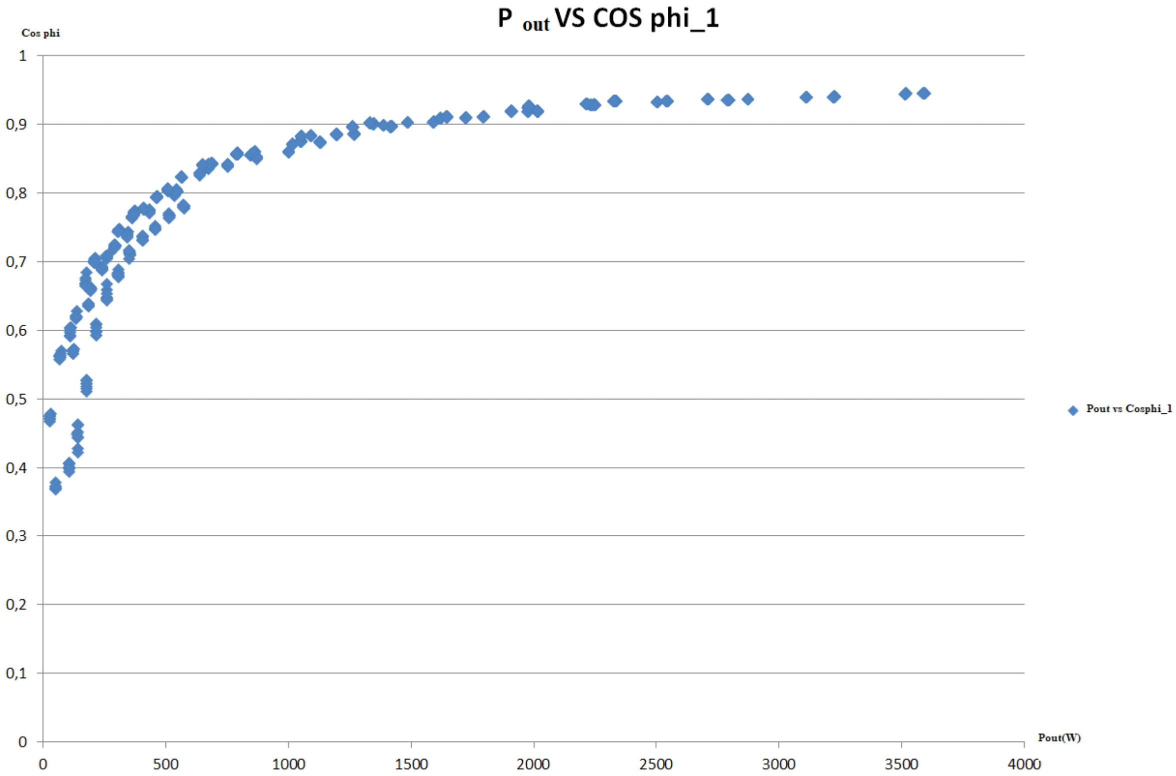


Fig. G.3: The power output VS Cos phi

Observation measurement 2:

1. The measurement results no longer contain noise.
2. The relationship between Puit vs cos phi is variable at low output power values, but is approximately linear for high output power values.
3. The maximum output power is not reached.

9.3: The relationship between power output vs efficiency

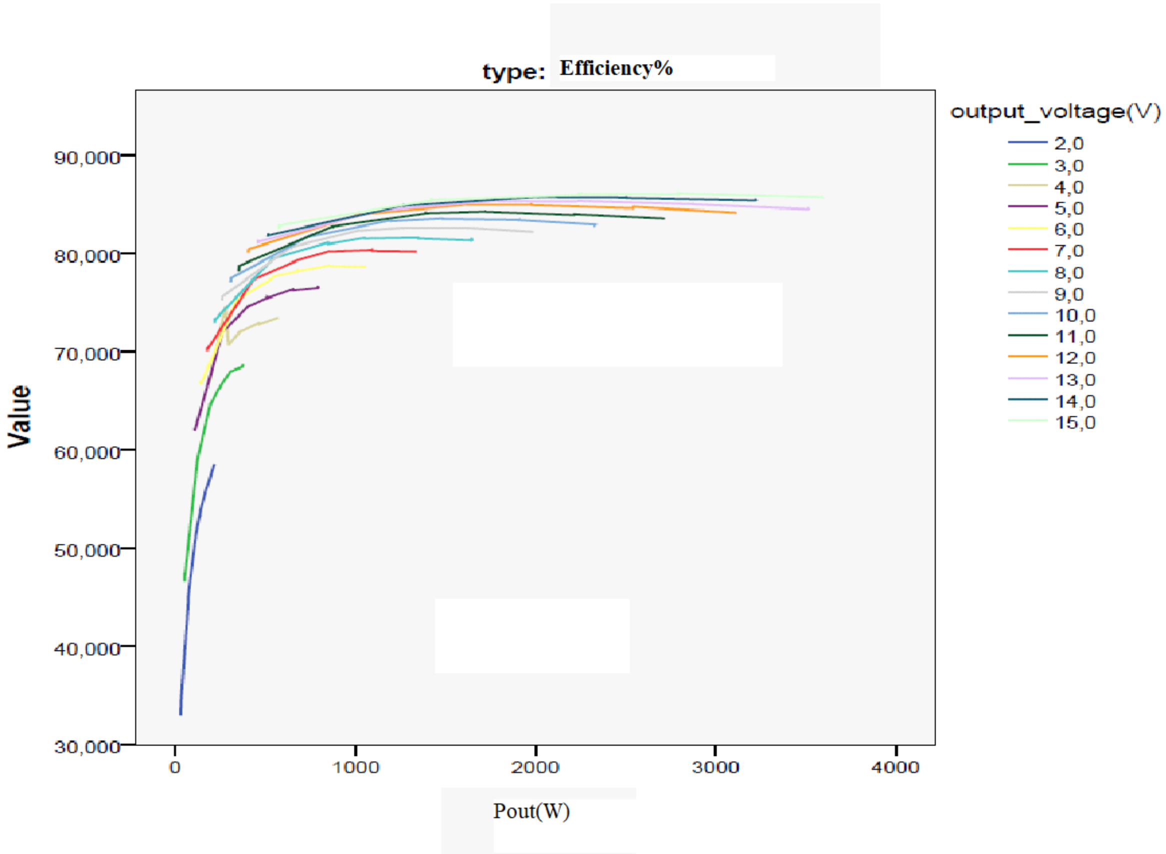


Fig. G.4: Power Output VS Efficiency

Observation measurement 3:

1. The results contain no more noise.
2. The relationship between power output and efficiency is not linear.
3. This graph is not important for calculating the input current limitation, but it is important for assessing the operation of the voltage source.
4. The maximum output power is not reached.
5. The higher the output voltage, the higher the efficiency, this graph clearly shows that relationship in this form.

10: Recommendations

Recommendation 1:

In previous tests (tests 1 and 2) the working method was such that the output voltages were changed manually. This appears to be a time-consuming process. It is now recommended to run the activities automatically. This can be done by optimizing the load resistance.

Recommendation 2:

The maximum power is not reached. The solution to this must be sought in optimizing the load resistance.

Recommendation 3:

Current charts should be optimized to make assessment easier and clearer.

11: Sub-conclusions

Several conclusions can be drawn:

Sub-conclusion 1:

Measurements no longer contain noise and give correct values. This means that the measured values can be used for assessment. The test setup is therefore suitable.

Sub-conclusion 2:

The relationships found in the graphs are approximately linear, but not complete. For this, the graphs must be optimized, so that the linearity becomes visible and the graph can therefore be assessed.

Sub-conclusion 3:

The variable load resistance now does not have the most optimal value, so that not all relevant resistance values are tested. Also, the maximum output power is not achieved. This requires an adjustment to the variable resistor.

12: Some results of 3xTDK-HWS

output_voltage(V)	output_current(A)	Puit()	IL1_N=(A)	IL2_N=(A)	IL3_N=(A)	Psum=(W)	COS_PHI[1]=	COS_PHI[2]=	COS_PHI[3]=	Rendement (%)
15,011834	38,411368	576,6250801	1,1844988	1,3013556	1,5731562	697,55352	0,77990896	0,77582064	0,822312	82,66391948
15,01278	38,42022	576,7943104	1,1934092	1,2907076	1,574447	696,31472	0,78123608	0,7729792	0,81987744	82,83528896
15,008742	38,249168	574,0718942	1,184608	1,2928386	1,5737008	695,68408	0,7800884	0,773634	0,82263504	82,51905006
15,010156	38,240624	573,9977318	1,1758656	1,3045056	1,5688342	694,55312	0,77781672	0,77618592	0,82139872	82,64274038
15,009372	38,223228	573,7066481	1,1922898	1,2831852	1,5711548	693,81568	0,77971176	0,76996128	0,8212628	82,68862533
15,013138	38,20614	573,5940523	1,1962716	1,2729992	1,5739896	693,2084	0,7820972	0,77096336	0,82112448	82,74482137
15,011574	38,197288	573,4014154	1,1848272	1,2801454	1,5827532	693,00528	0,78074304	0,77185192	0,8230304	82,74127658
15,01376	38,188744	573,3566371	1,1937778	1,2815158	1,5604938	692,14688	0,7827176	0,77318016	0,81928888	82,83742276
15,01204	94,676472	1421,286985	2,7148572	2,7858312	3,0228624	1663,662	0,89713384	0,89068864	0,90020152	85,43123451
15,013448	94,659688	1421,168303	2,7252646	2,7794444	3,0170366	1662,7578	0,89702744	0,89100272	0,90000576	85,47055401
15,01549	94,608728	1420,596409	2,7127766	2,777104	3,0270358	1661,3146	0,8970512	0,89077992	0,89992736	85,5103789
15,014238	94,52328	1419,195022	2,7030214	2,7862452	3,022706	1660,2082	0,89603408	0,8913612	0,90056856	85,48295464
15,012554	94,239696	1414,778525	2,71419	2,7789598	3,0198416	1658,1926	0,89642208	0,89085568	0,90024384	85,32051857
15,008946	94,205816	1413,930005	2,7098774	2,7761968	3,0220264	1657,392	0,89693368	0,89084568	0,90009976	85,31053639
15,012388	94,154552	1413,484667	2,7114334	2,7750962	3,0140866	1656,0182	0,89713608	0,89081088	0,89994576	85,35441619
15,01161	94,129216	1413,03108	2,709403	2,7669124	3,0212398	1655,1768	0,89673064	0,89081272	0,90021024	85,37040153
15,010352	149,9419	2250,680699	4,175754	4,1831484	4,4777188	2615,0778	0,92875288	0,92380912	0,9321644	86,06553497
15,012388	149,89216	2250,239264	4,1832384	4,188622	4,444626	2611,8408	0,9286232	0,92405448	0,93166752	86,15529951
15,01365	149,83326	2249,544124	4,1863636	4,189684	4,462392	2610,489	0,92910632	0,92428824	0,93219616	86,17328493
15,01349	149,76672	2248,521153	4,1820928	4,1909792	4,4599912	2611,0282	0,92868992	0,9245336	0,93216872	86,11631054
15,01522	149,6999	2247,776932	4,1773832	4,188496	4,4510324	2607,9956	0,92895456	0,9243572	0,93178864	86,18791122
15,015376	149,68342	2247,552832	4,1826544	4,18558	4,4691888	2610,3718	0,92940008	0,92420768	0,93236296	86,10087009
15,011412	149,4352	2243,233355	4,175452	4,185208	4,4400128	2605,1796	0,92877928	0,92453104	0,93179904	86,10666821
15,008424	149,3934	2242,15949	4,1765612	4,18269	4,4360656	2608,0492	0,9289524	0,92450616	0,9317048	85,97075124
15,012502	186,15974	2794,723469	5,1497676	5,1630736	5,463952	3247,4536	0,93583528	0,93187976	0,93789568	86,05891918
15,013442	186,18476	2795,274096	5,1568712	5,1637872	5,4378052	3245,7136	0,93603792	0,93187496	0,9378552	86,12201938
15,015332	186,0688	2793,884807	5,15329	5,163208	5,458818	3247,0684	0,93605176	0,93192768	0,93779464	86,04330007
15,013764	186,03584	2793,098197	5,1666992	5,1605716	5,4498312	3244,8536	0,9359796	0,93182552	0,93773816	86,07778783
15,014698	185,96138	2792,15396	5,1666392	5,158398	5,4609372	3244,683	0,93605576	0,93205736	0,93786456	86,05321261
15,014698	185,89546	2791,164191	5,1588072	5,1516248	5,466524	3242,5796	0,93599288	0,9319344	0,93803264	86,07850958
15,013598	185,85366	2790,332138	5,1492632	5,1462588	5,4468676	3240,3696	0,93603064	0,93187744	0,93771696	86,11153919
15,011126	185,58856	2785,893258	5,141812	5,1360412	5,4257292	3237,5938	0,93594448	0,93151304	0,937862	86,04826394
15,012694	239,35778	3593,405108	6,5942736	6,5790736	6,8887144	4197,2604	0,94565536	0,94224752	0,94807424	85,61310868
15,014892	239,30896	3593,198189	6,5714952	6,5604696	6,8609152	4194,372	0,94533696	0,9421452	0,94762216	85,66713179
15,015358	239,15424	3590,986531	6,5775724	6,5668092	6,8348992	4190,7036	0,94529448	0,9424088	0,9476536	85,68934655
15,014736	238,94214	3587,653151	6,5604912	6,55534	6,8379304	4186,1792	0,9451052	0,9420256	0,94745792	85,70233093
15,013324	238,88508	3586,459105	6,561126	6,5543304	6,839072	4184,6132	0,94523576	0,9421612	0,94746416	85,70586894
15,013478	238,85242	3586,005553	6,5623312	6,5609184	6,8367992	4182,4028	0,94509672	0,94241232	0,94739744	85,7403202
15,01379	238,80358	3585,346801	6,560118	6,5668468	6,8302536	4182,3192	0,94503872	0,94231608	0,94726144	85,72628319

Table G.2: Some results of test 2

13: Some graphs of 3xTDK-HWS

- *Cos phi vs Puit for Phase 1*

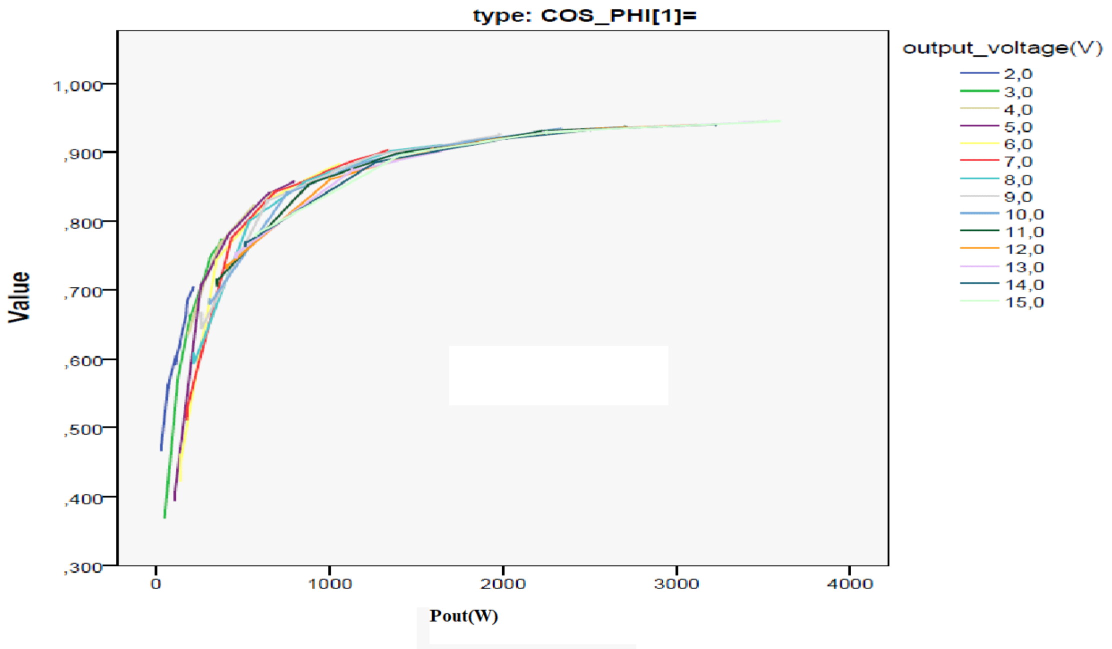


Fig. G.5: Cos phi vs Puit for phase 1

- *Cos phi vs Puit for phase2*

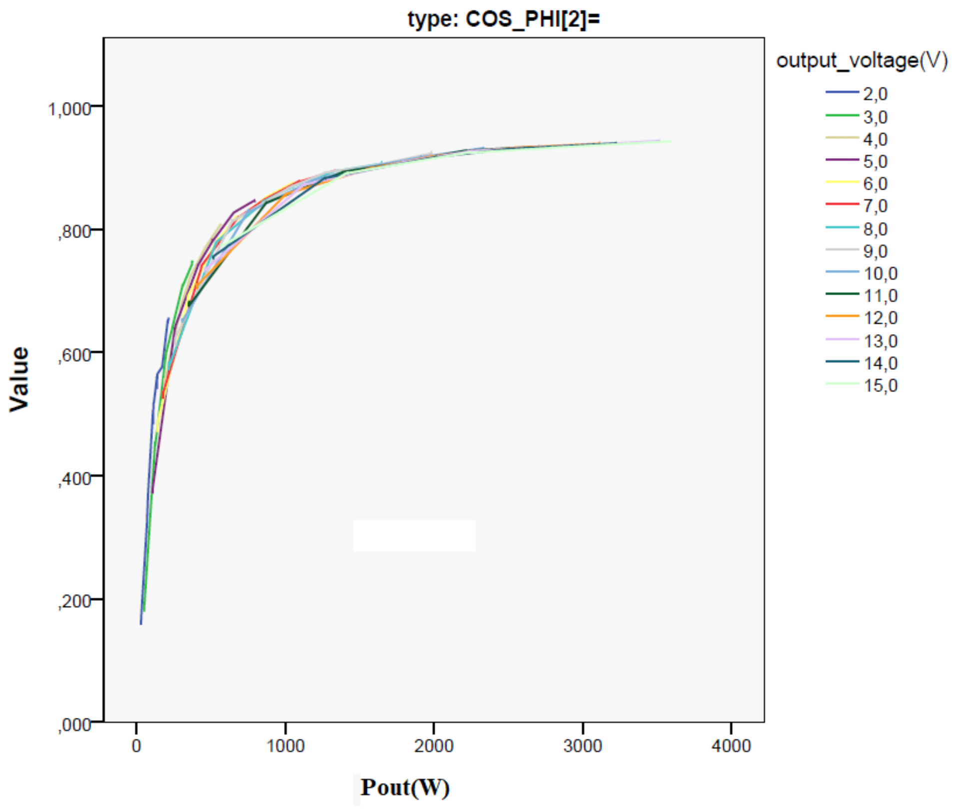


Fig. G.6: Cos phi vs Pout for phase 2

- *Cos phi vs Puit for fase 3*

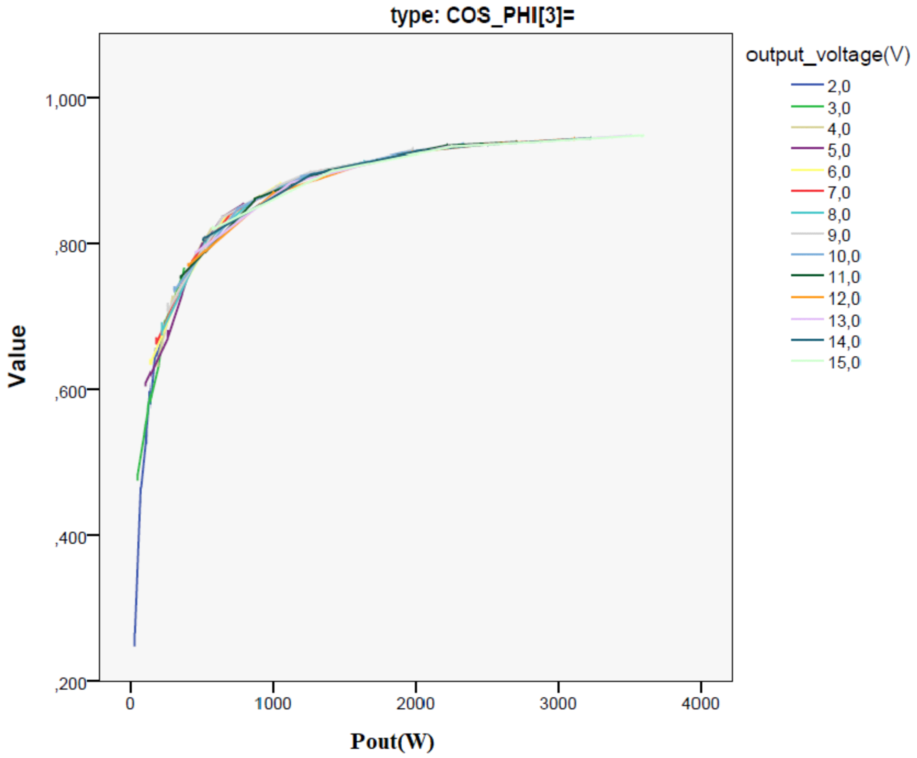


Fig. G.7: Cos phi vs Puit for phase 3

- *I fase vs Puit for fase 1*

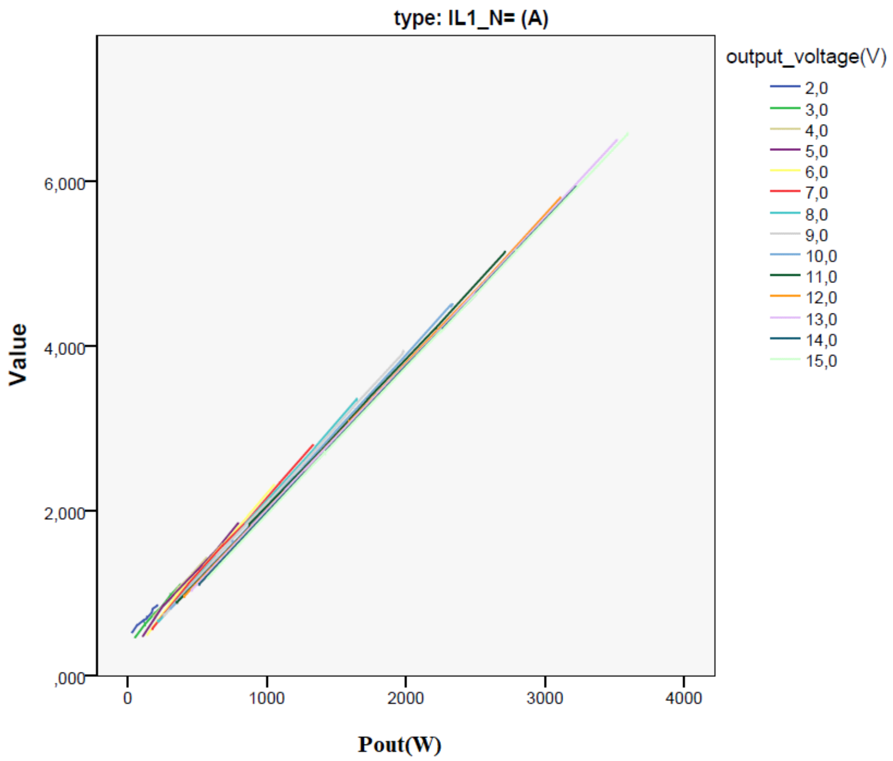


Fig. G.8: I fase vs Puit for phase 1

- *I fase vs Puit voor fase 2*

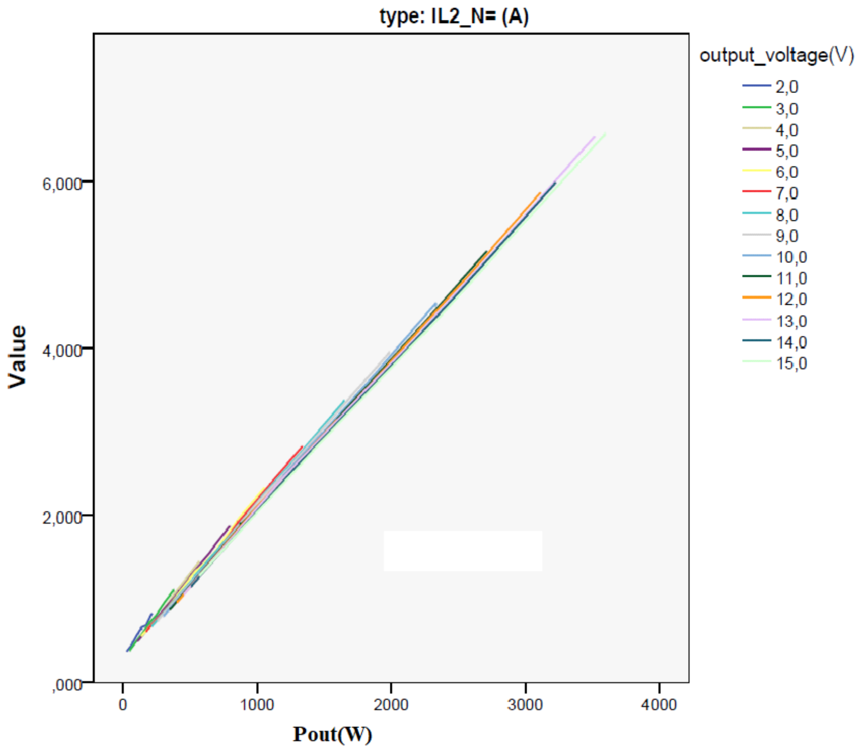


Fig. G.9: I fase vs Puit for phase 2

- *I fase vs Puit voor fase 3*

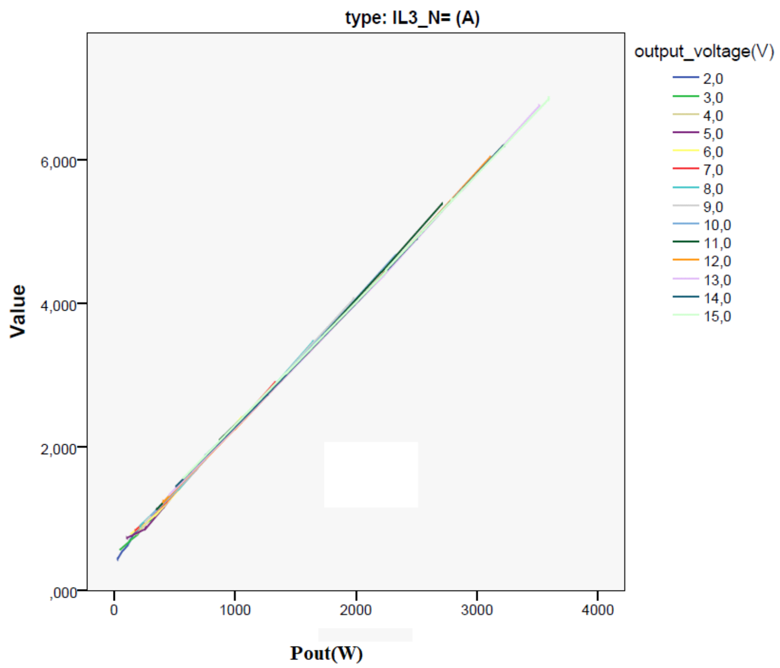


Fig. G.10: I fase vs Puit for phase 3

- *Psum vs Puit*

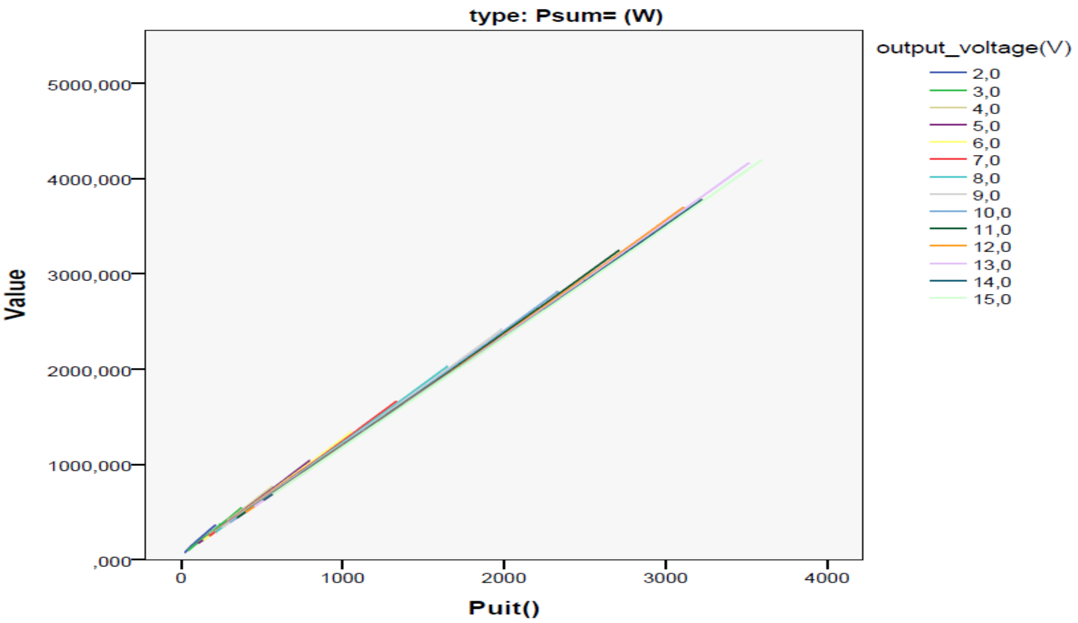


Fig. G.11: Psum vs Puit

- *Rendement vs Puit*

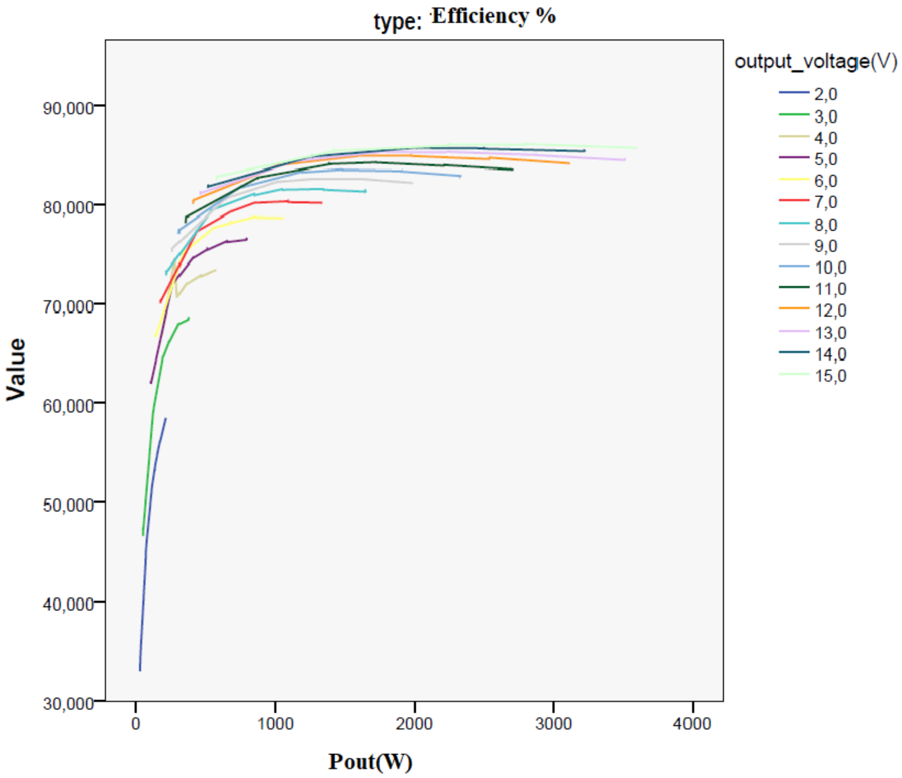


Fig. G.12: Efficiency vs Pout

Appendix H – Optimization rating graphics

1: Introduction

It has been found that it is necessary to standardize the charts in order to standardize the assessment.

2: Measurement results Puit vs efficiency

The efficiency of the equalizer is an important specification for the customers and should not be missing on a data sheet. The return has approximately a constant value as Puit increases. This is clearly visible at high voltage (Results of Test 2 shown).

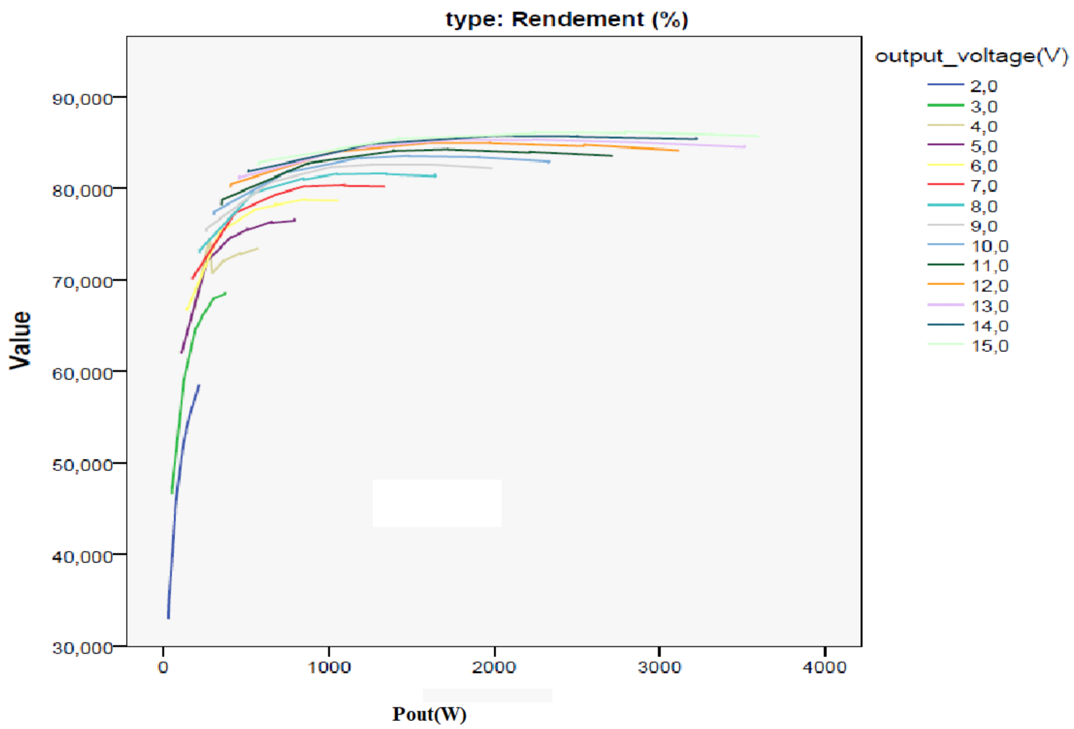


Fig. H.1: Pout VS efficiency

3: Measurement results Pout vs Cos phi

The Cos phi is an important specification because this parameter indicates how much does the system of a reactive power generate.

The effect of the Cos phi is variable at the beginning of the low values of the output power, which depends on the values of the output voltage. For higher power, Cos phi becomes approximately constant for all values of the output voltage. A graph is created according to the measurement results.

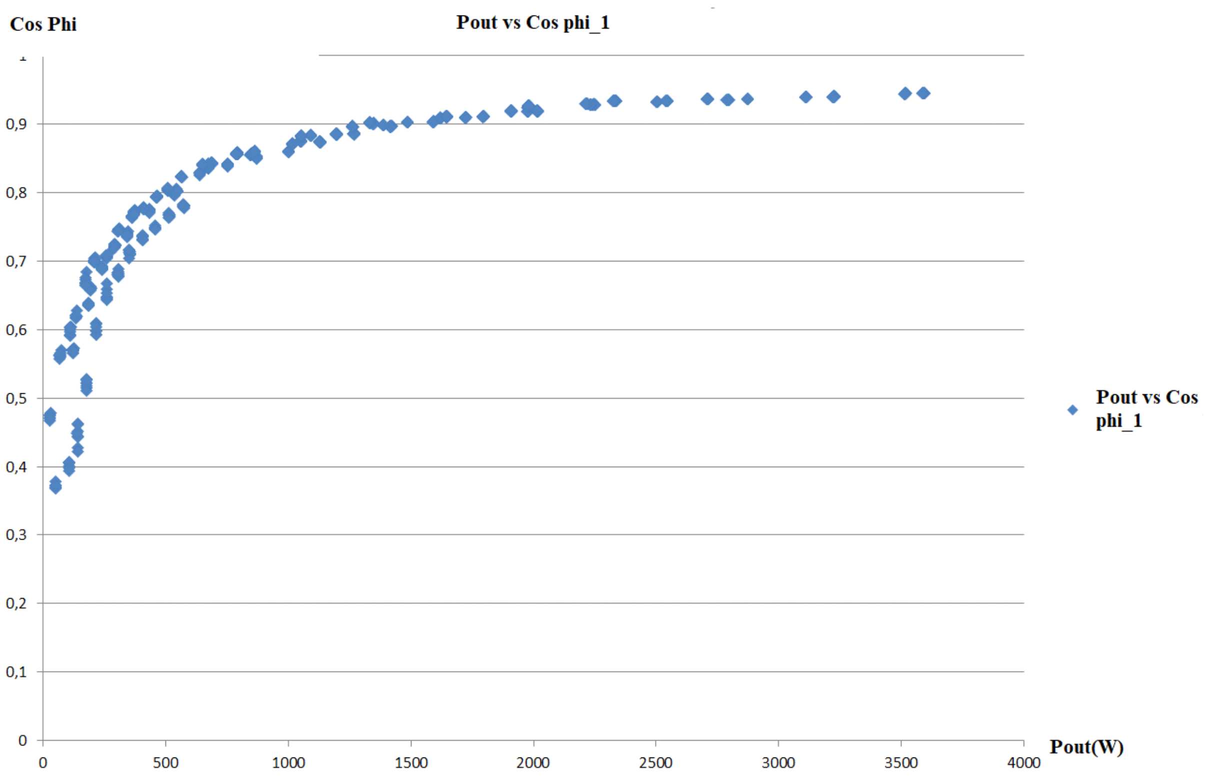


Fig. H.2: Pout vs Cos phi for Phase 1

4: Measurement results of Puit vs If

This graph should result in a formula to calculate based on the output current. This formula can be used for the input current limitation.

At low values of the output power, the phase current gets different values which depends on the output voltage. For high values, the If becomes approximately linear (without spreading). This can be seen in the following formula:

$$I_{fase} = \frac{1}{3\,\eta\,V_{phase}\cos\emptyset}\,P_{out} \ldots (H.1)$$

The graph of If and Puit is drawn according to the formula If of return inversion and Cos phi inversion. The graph below shows all measured variables. See the effect of Cos phi in the following figure:

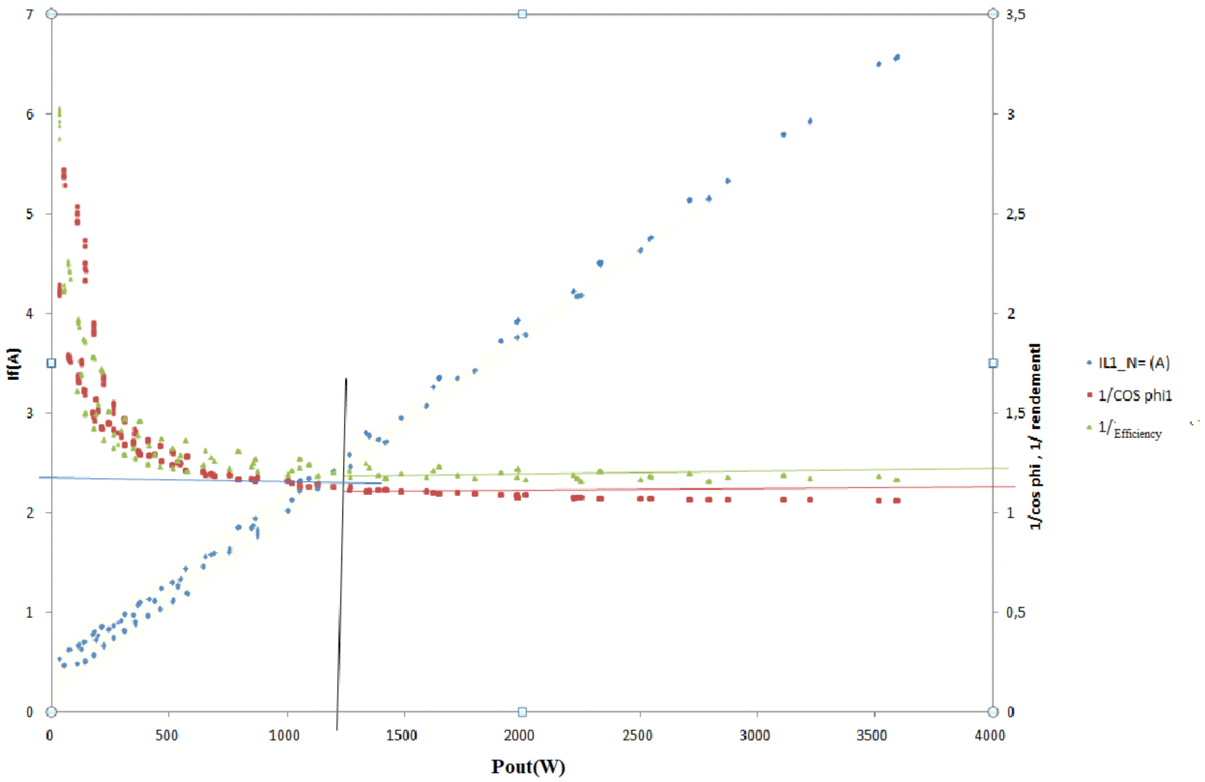


Fig. H.3: The relationship between power output, Cos phi and efficiency

Above 1000 W the values of Cos phi and efficiency are almost constant and below 1000 W the values are more spread out, as can clearly be seen in the fig above. If it is almost linear as a function of Pout for Pout greater than 1000 W:

$$y = a\,x + b \qquad valid\ when\ Pout\ >\ 1000\,W$$

Appendix I – Results and graphs of test 3

1: Introduction

In test 3, the same steps are taken as in tests 1 and 2, but these steps are improved by a new insight obtained by tests 1 and 2. The purpose of test 3 is to calculate the limitation of the power, i.e., the input current is no more than 16 A per phase.

2: Improvements with respect to test 2

Certain recommendations have been made for test 3. The following changes have been made:

- A new program has been made for the automation by PLC Alpha 2. All manual processing is now a thing of the past, because that was time-consuming. See Appendix G- Results and graphs, Test 2-Recommendation 1.
- A new variable load resistor is connected in parallel, which gives greater power. See Appendix G-Results and graphs, Test 2-Recommendation 2.
- Create clear graphs via multiple measuring points. See Appendix G- Results and graphs, Test 2-Recommendation 3.
- Optimization Rb and optimization graphs.

3: Theoretical expectation of measurement results

In test 2, 3 graphs and the theoretical expectation were assessed. Test 3 shows the same graphs and expectations. See Appendix G – Test 2 Results and graphs of test 2.

4: Block diagram

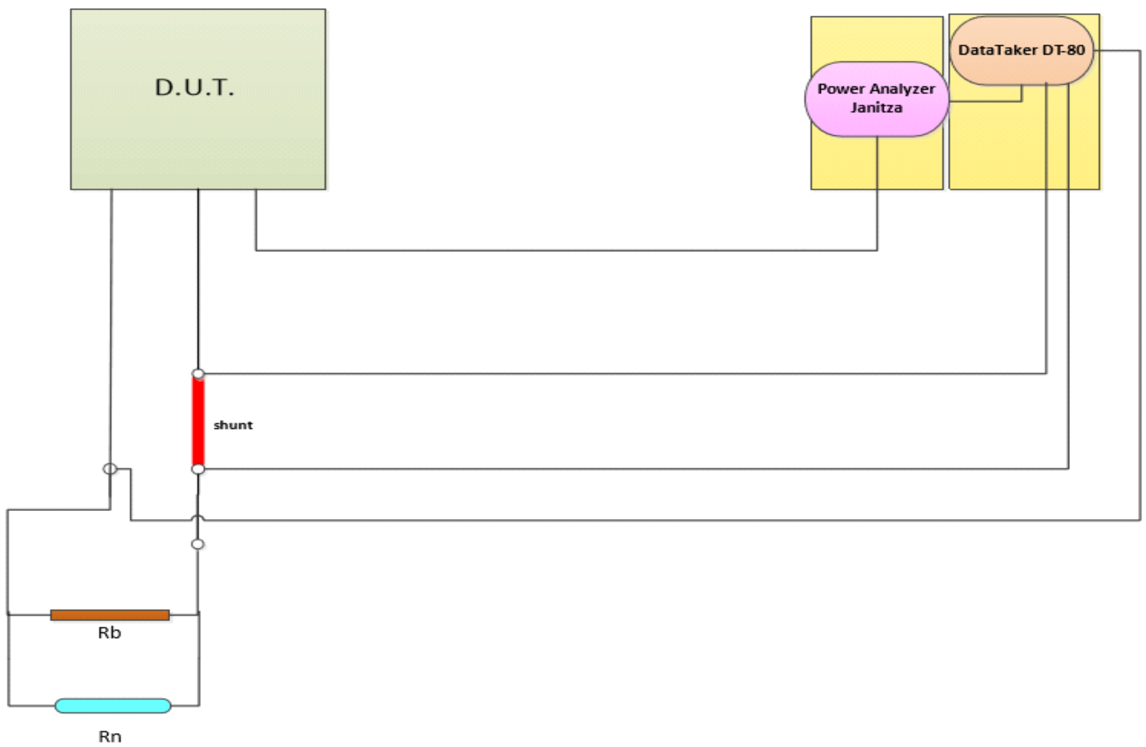


Fig. I.1: Block diagram of the test 3

5: The purpose of the test

This is also identical to that in section 5. See Appendix G – Results and graphs of test 2.

6: Used measuring equipment

This is also identical to that in section 6. See Appendix G – Results and graphs of test 2.

7: The measurement

This is also identical to that in section 7. Appendix G- results and graphs of test 2.

8: The modbus address

This is also identical to that in section 8. See Appendix G – Results and graphs of test 2.

9: The results and the graphs

- *The output power vs the input current*

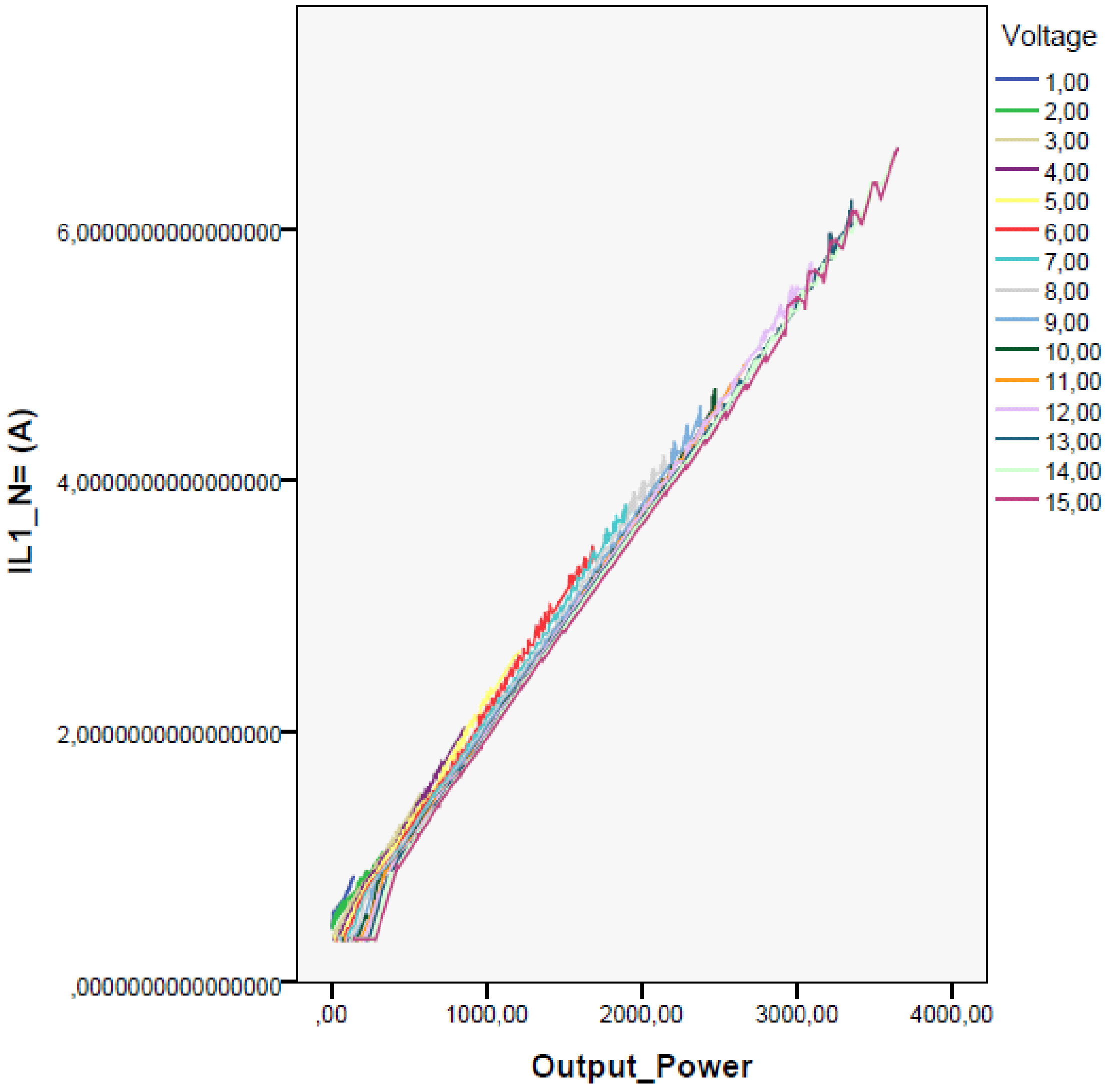


Fig. I.2: The output power(W) vs the input current(A)

- *Observation measurement 1:*

1. The measurement results no longer contain any noise at all.
2. The relationship between output power and input current is approximately linear approach.
3. This graph can be used to calculate the input current at a given
   output current.
4. The maximum output power has been reached. A new load Rn has been used.

- *The relationship between the power output and Cos phi*

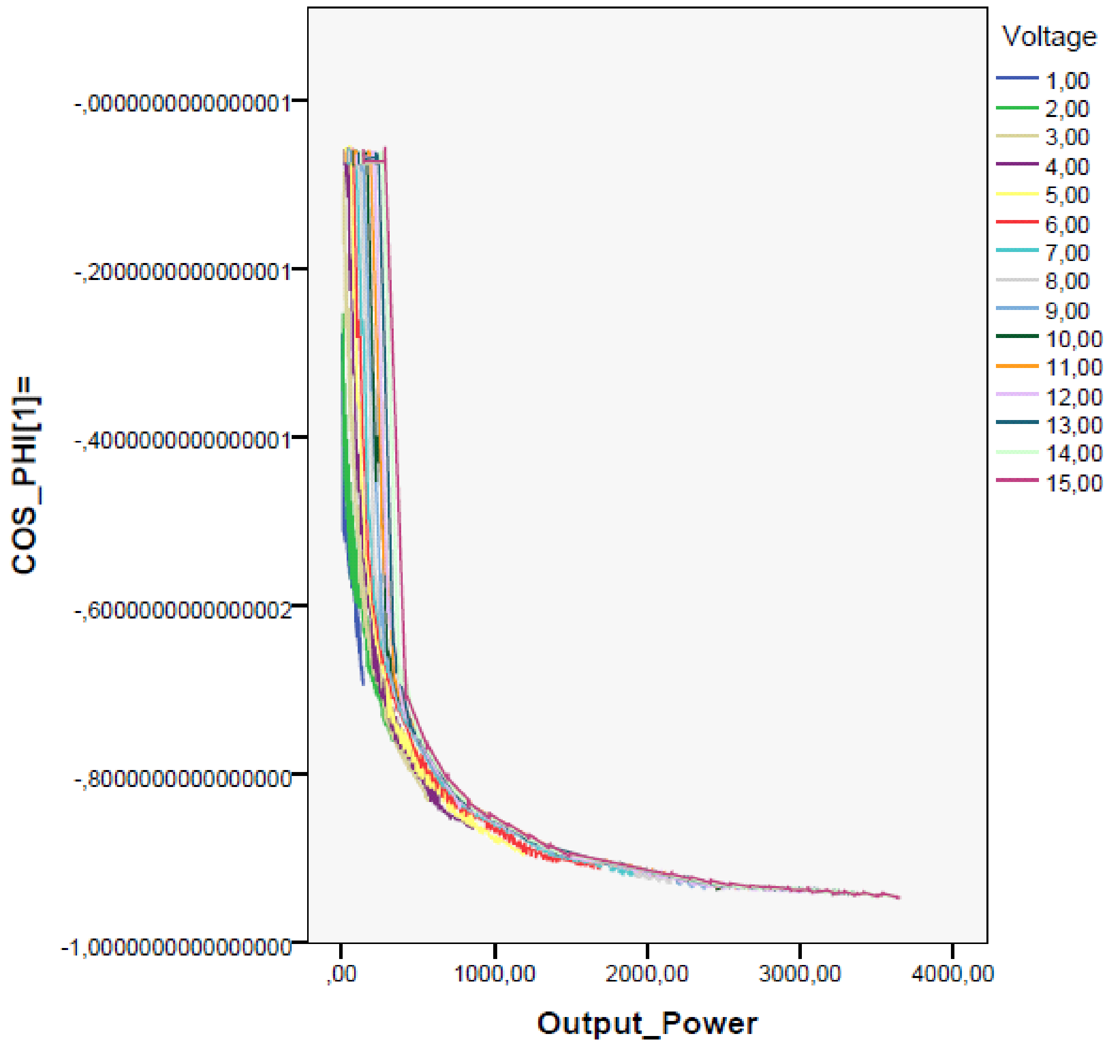


Fig. I.3: The output power(W) vs Cos phi

- *Observation measurement 2:*

1. The measurement results no longer contain any noise at all.
2. The relationship between Puit vs cos phi is variable at low output power values, but
   for high values approximately linear.
3. The maximum output power has been achieved by using a new load Rn.

- *The relationship between power output vs efficiency*

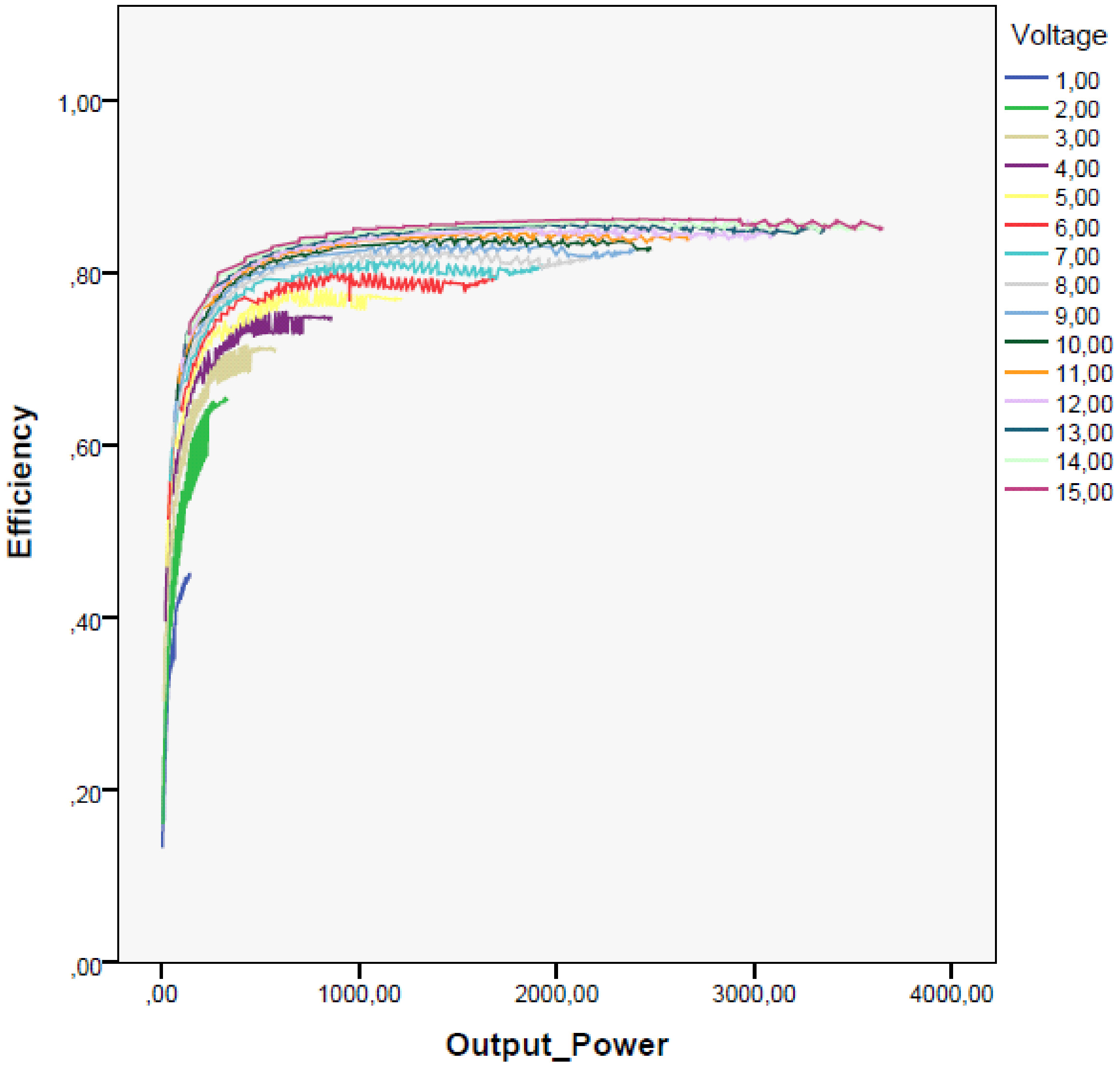


Fig. I.4: The power output (W) vs efficiency

- *Observation measurement 3:*

1.The measurement results no longer contain any noise at all.

2. The relationship between power output and efficiency is not linear.

3. This graph is not important for calculating the input current limitation, but for assessing the operation of the voltage source.

4. The maximum output power has been achieved by using a new load Rn.

10: Some results (3xHWS 1500-15)

Output_Voltage[V]	Output_Current[A]	Output_Current_Rn (A)	Total output current	V L1_L2= (VAC)
15,000318	9,373322	186,58584	195,95916	394303,56
15,00267	9,477692	186,70974	196,18744	394196,6
15,002992	9,521638	186,71798	196,23962	394104,28
14,999534	9,521638	186,64382	196,16546	393827,12
15,00079	9,565278	186,64382	196,2091	394062
15,00173	9,573822	186,6603	196,23414	393999,6
15,00471	9,591218	186,62704	196,21826	393837,6
15,002094	9,44378	186,51594	195,95972	393565,64
15,000676	9,46148	186,4906	195,95208	393337,12
15,002094	9,47033	186,71398	196,18432	393300,08
15,002406	9,487724	186,7555	196,24322	393691,4
15,003028	9,487724	186,62336	196,11108	393531,24
15,001772	9,53106	186,59008	196,12116	393629,72
15,004292	9,548454	186,50738	196,05584	394206,48
15,00413	9,53991	186,49914	196,03906	393742,04
15,002716	18,80474	186,367	205,17176	394089,48
15,003662	18,90026	186,44116	205,34144	394042,04
15,004758	18,926506	186,44116	205,36768	394421,48
14,999162	18,771668	186,24054	205,0122	394084,08
15,002928	18,806458	186,32324	205,1297	393791,28
15,004178	18,815002	186,40594	205,22094	393521,32
15,00355	18,823852	186,44714	205,271	392603,64
15,004802	18,832092	186,48864	205,32074	392703,28
15,003712	18,849488	186,47186	205,32136	393018,32
15,004178	18,884278	186,47186	205,35614	392998,2
15,004802	18,875732	186,54664	205,42236	392901,64
15,001634	18,735084	186,35868	205,09376	393253,84
15,001166	18,76957	186,37516	205,14472	393229,8
15,002262	18,761024	186,39988	205,16088	393294,8
15,002574	27,995644	186,45786	214,4535	392884,36
15,003208	28,125954	186,44138	214,56732	393571,32

Table I.1: Some results of test 3

11: Some graphs

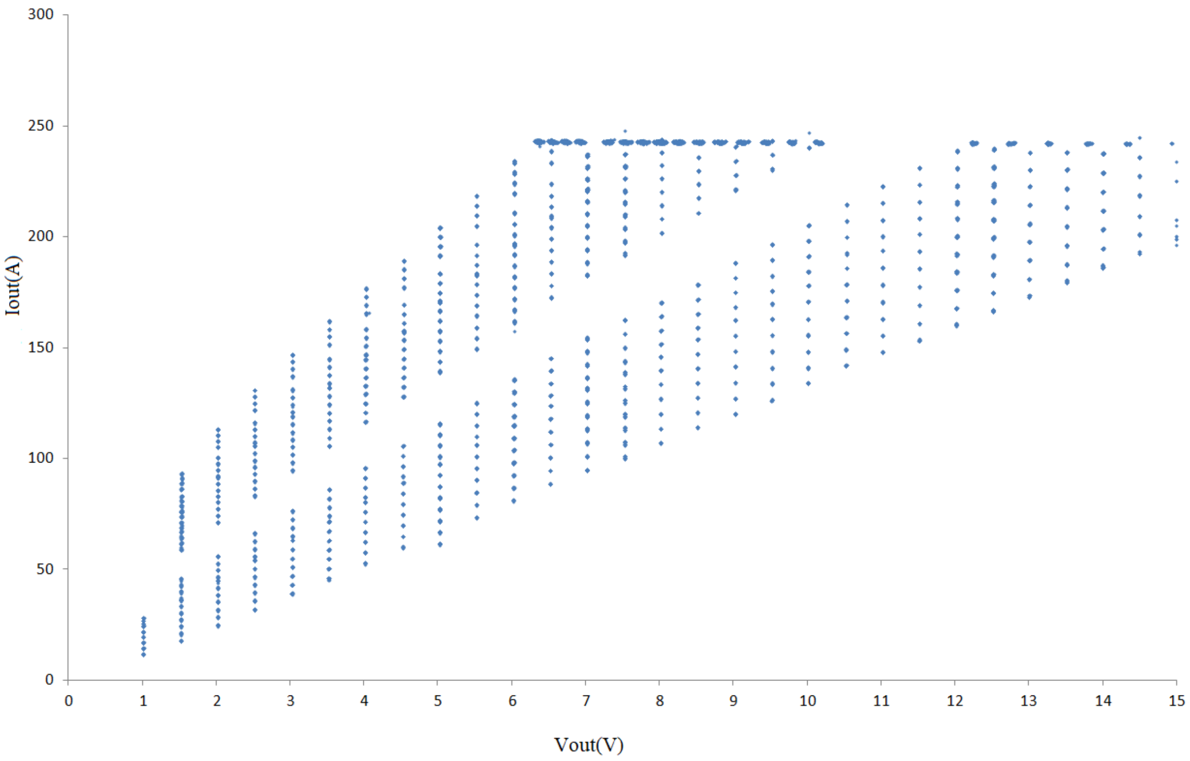


Fig. I.5: The output voltage vs output current

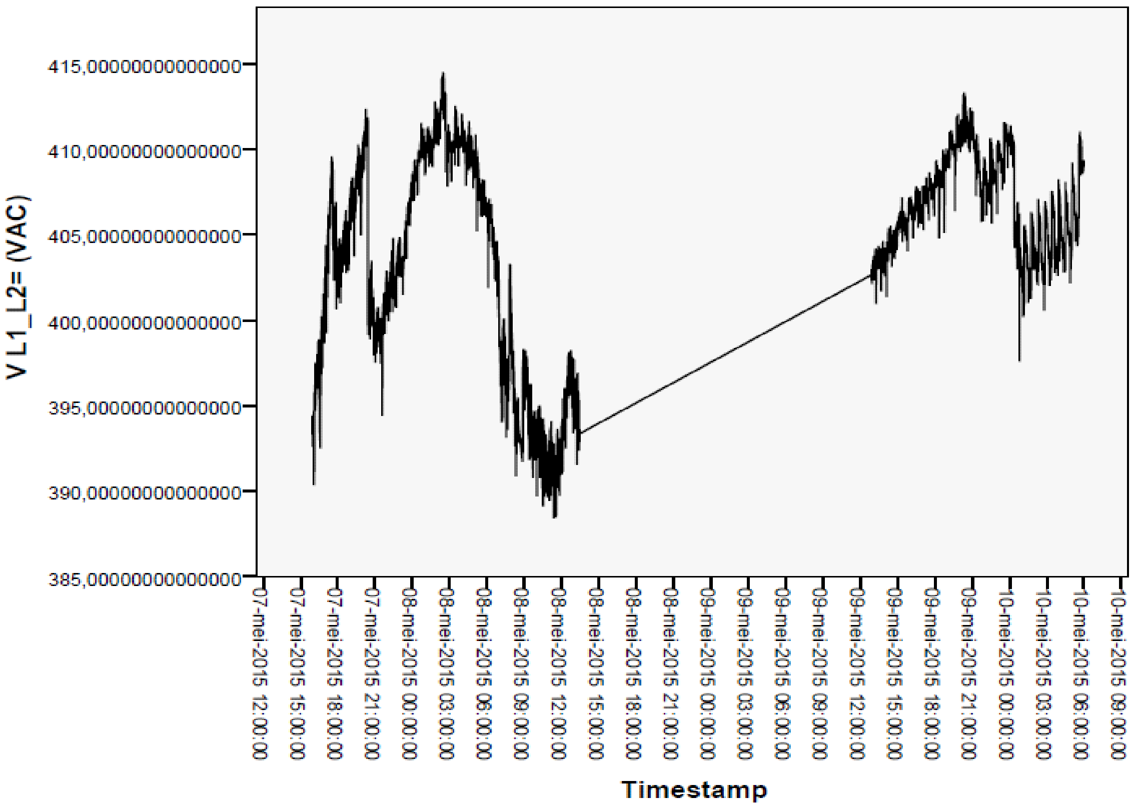


Fig. I.6: The output voltage vs time

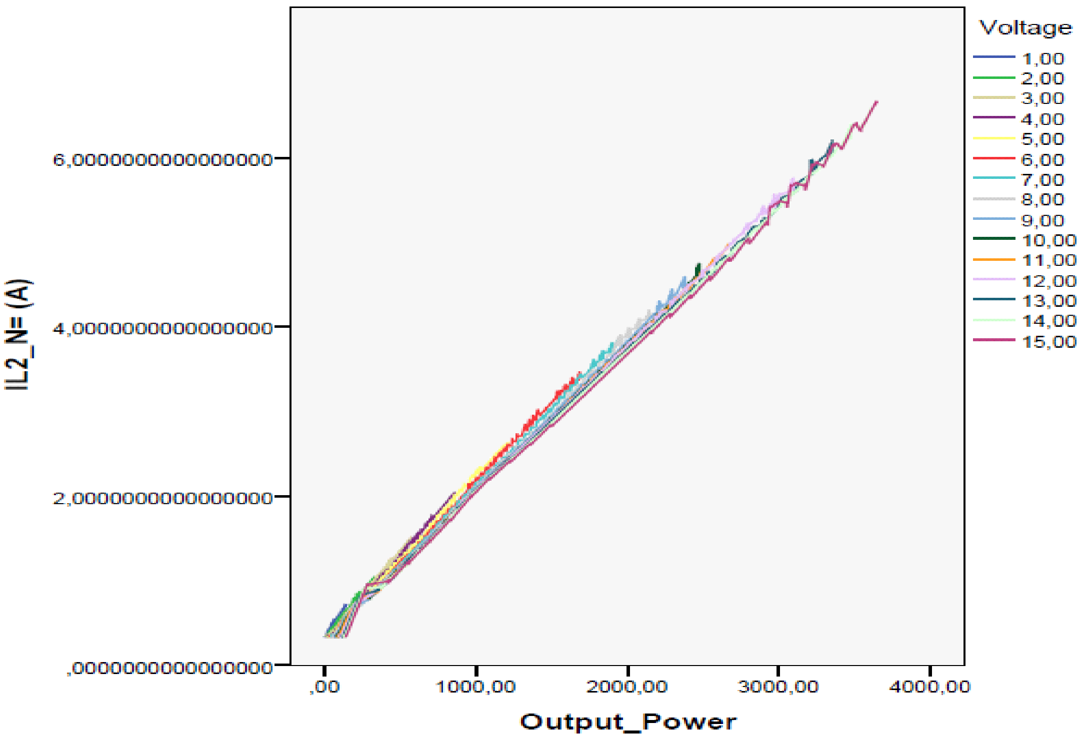


Fig. I.7: Input current of phase 2 vs output power

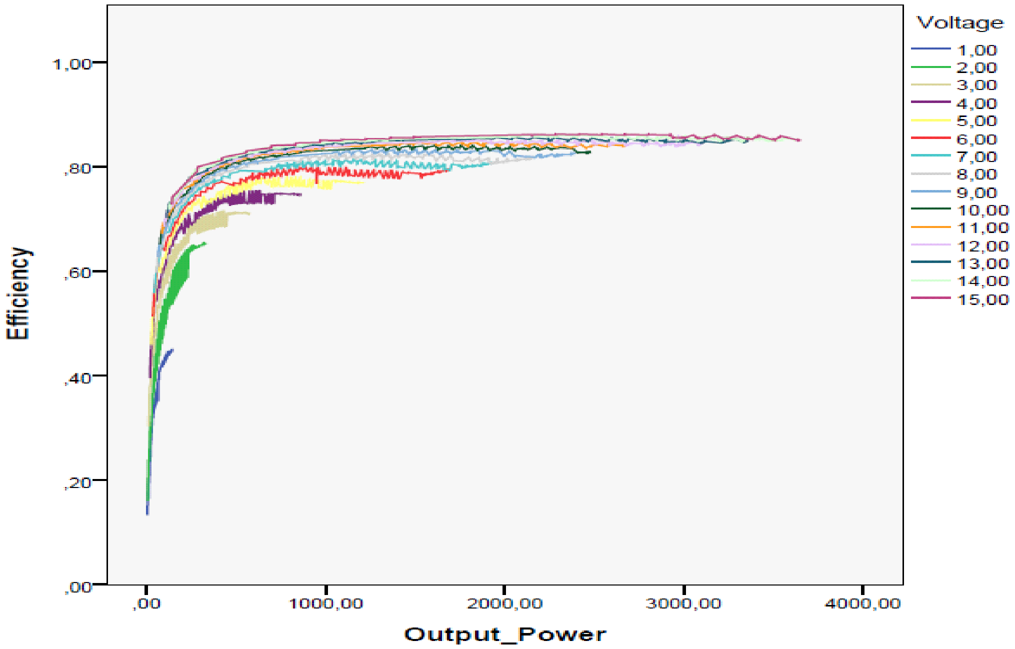


Fig. I.8: Power output vs efficiency

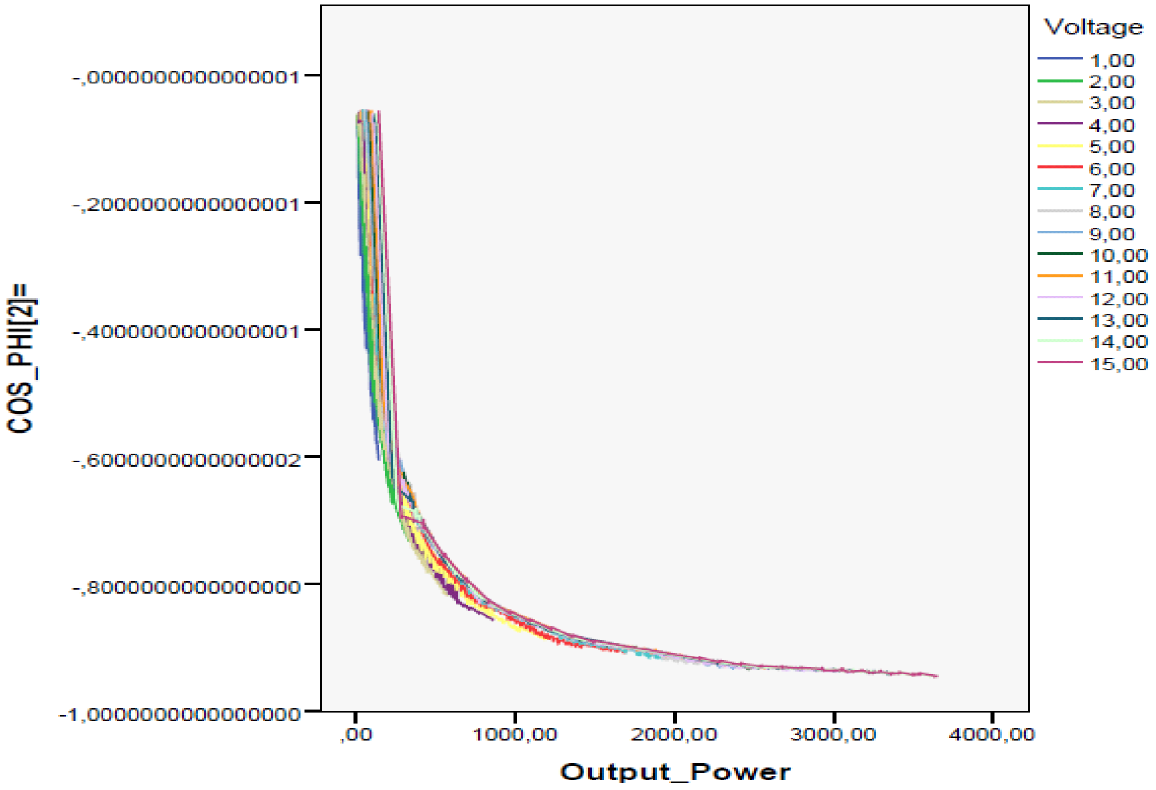


Fig. I.9: Output power vs cos phi of phase 2

Appendix J – Results and graphs of current harmonic

J.1: current harmonic

The harmonic current for the second harmonic is approximately zero.

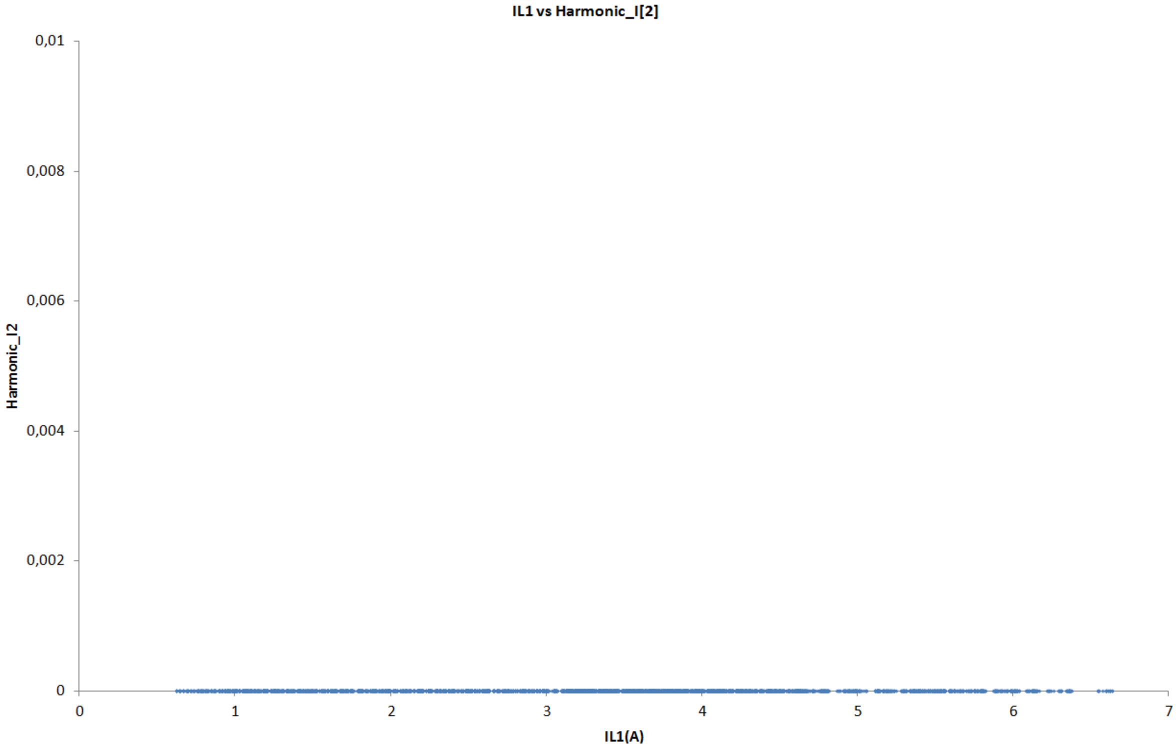


Fig. J.1: Second harmonic of current

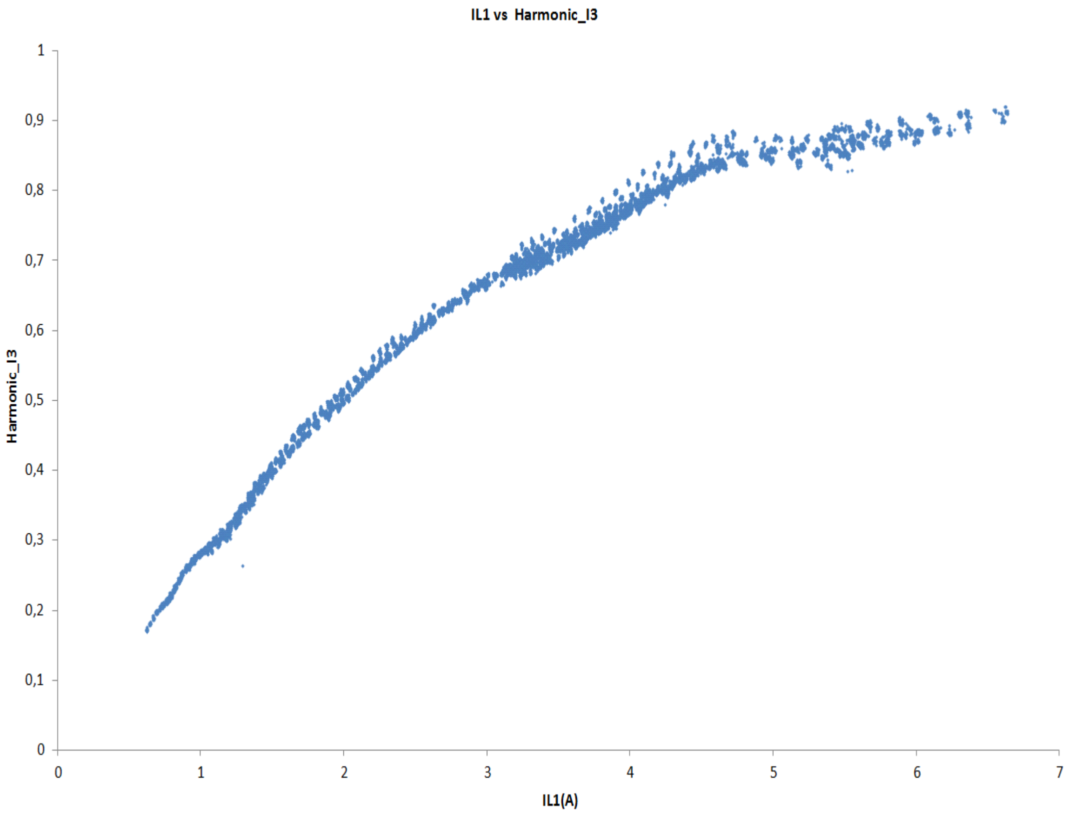


Fig. J.2: Third harmonic of current

For the current harmonics of 2-7 see the following figure:

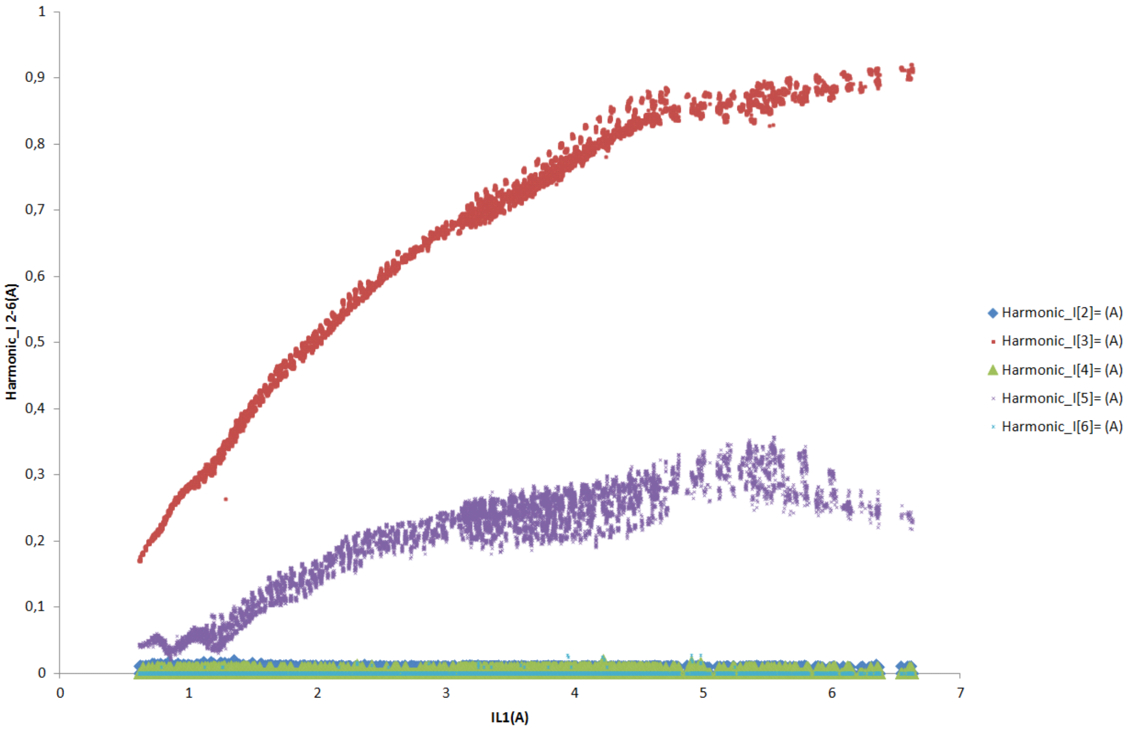


Fig. J.3: Current harmonics from 2-7

The results of the harmonics and the data of standard ICE61000-3-2 are compared and determined. The results are within the norm.

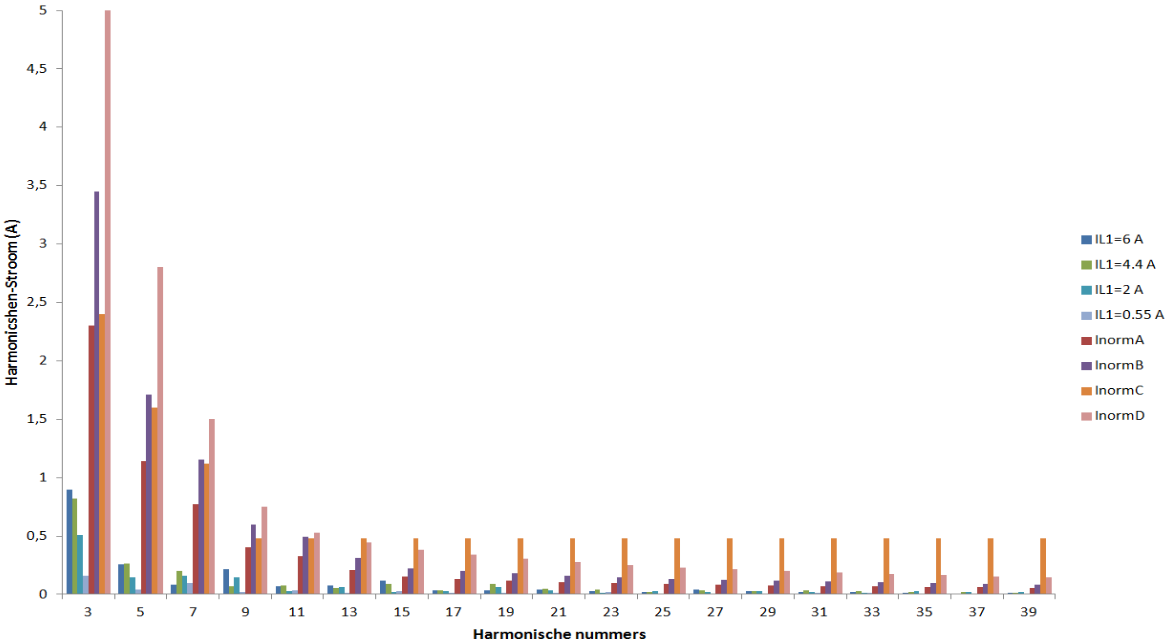


Fig. J.4: Current harmonics of 3-39

J.2: Sub-conclusion

HWS Harmonic current is within the standard of ICE61000-3-2.

Appendix K – Results and graphs of other tests

K.1: Test 4

- *Some results (3xHWS 1500-24)*

Output_Voltage[V]	Output_Current[A]	Output_Current_Rn(A)	Total output current	V L1_L2= (VAC)	V L2_L23 (VAC)	IL1_N= (A)
23,931618	12,118034	-0,116158	12,001878	398101,64	398101,64	1233,0284
23,934442	12,214166	-0,028877	12,185288	398504,56	398504,56	1238,6382
23,931752	12,257806	0,005913	12,263718	398344,36	398344,36	1271,2648
23,933094	12,2752	0,058708	12,333908	398021,32	398021,32	1253,6114
23,935788	12,30114	0,076103	12,377244	398092,88	398092,88	1227,2042
23,932422	12,34478	0,067253	12,412034	398211,52	398211,52	1246,8096
23,933094	12,371026	0,110893	12,481918	397908,84	397908,84	1300,0538
23,93258	12,20028	-0,051613	12,148666	398238,08	398238,08	1264,8874
23,933388	12,217674	-0,025368	12,192308	398246,8	398246,8	1315,913
23,932044	12,24392	0,000877	12,244798	398242,12	398256,28	1252,2206
23,931234	12,252464	0,018272	12,270738	398283,2	398283,2	1257,3998
23,9346	12,26986	0,000877	12,270738	398364,36	398364,36	1269,057
23,933926	12,27871	0,035667	12,314378	397719,92	397727,2	1227,191
23,935408	12,30465	0,053368	12,358018	397985,28	397985,28	1258,853
23,933654	12,330894	0,079308	12,410202	398019,48	398019,48	1250,7412
23,938636	12,330894	0,105553	12,436448	398147,64	398147,64	1248,0416
23,93285	24,2062	-0,016518	24,189682	397232,48	397232,48	1452,9984
23,933926	24,29287	0,061913	24,354782	397551	397551	1433,4534
23,934328	24,30172	0,114403	24,416122	397202,08	397322,16	1406,6142
23,929744	24,135438	-0,043945	24,091492	396909,72	396909,72	1421,5414
23,933242	24,178772	-0,03479	24,143982	396594,68	396605,64	1407,2434
23,933646	24,178772	-0,00885	24,169922	396539,44	396539,44	1371,8866
23,930954	24,196166	0,026245	24,222412	396678,92	396678,92	1422,9236
23,934054	24,204712	0,04364	24,248352	396577,36	396714,88	1457,5596
23,934592	24,196166	0,04364	24,239808	397428,48	397428,48	1435,9138
23,935128	24,222106	0,08728	24,309388	397375,76	397375,76	1412,7676
23,935396	24,230652	0,104675	24,335328	397377,48	397377,48	1397,8774
23,9358	24,239502	0,104675	24,344178	397885,16	397885,16	1456,8346
23,93217	24,126586	-0,017395	24,109192	397688,2	397688,2	1446,2386
23,933922	24,152832	0	24,152832	397885,2	397885,2	1436,8242
23,93352	24,161072	0,00885	24,169922	397855,44	397790,6	1417,0422

23,933652	24,195862	0,0354	24,231262	397597,8	397597,8	1414,7114
23,93042	36,17462	-0,113525	36,061096	397432,92	397432,92	1852,8952
23,934728	36,269836	-0,02594	36,243896	397022,36	397022,36	1835,9816
23,936608	36,339112	-0,03479	36,30432	394833,76	394833,76	1836,2022
23,936882	36,365052	0,02655	36,3916	396767,6	396767,6	1845,6702
23,93607	36,365052	0,052795	36,417848	397015,08	397015,08	1880,8202
23,9354	36,390992	0,07019	36,46118	397103,6	397103,6	1808,371
23,938222	36,417236	0,087585	36,50482	396624,36	396624,36	1832,9148
23,938896	36,42578	0,10498	36,53076	396566,08	396566,08	1838,839
23,936474	36,43402	0,113525	36,547548	396388,32	396388,32	1843,0556
23,934784	36,286888	-0,033913	36,252976	396159,84	396159,84	1817,7916
23,934514	36,295432	-0,016518	36,278916	396614,6	396614,6	1844,065
23,935724	36,312524	0,000877	36,3134	396452,12	396452,12	1821,5392
23,935864	36,304284	0,009727	36,314012	396690,52	396650,6	1830,6872
23,935998	36,329916	0,018272	36,348192	396628,48	396628,48	1834,9106
23,933846	36,356164	0,018272	36,374436	396410,36	396410,36	1843,0722
23,930348	48,184164	-0,103798	48,080368	396780,64	396780,64	2305,9624
23,93707	48,2275	-0,007668	48,219832	396510,96	396510,96	2359,6072
23,93855	48,253136	0,000877	48,254012	396878,36	396878,36	2337,0508
23,93828	48,253136	0,027122	48,28026	396550,52	396550,52	2326,9314

Table K.1: Some results of test 4

- *Graphs of test 4*

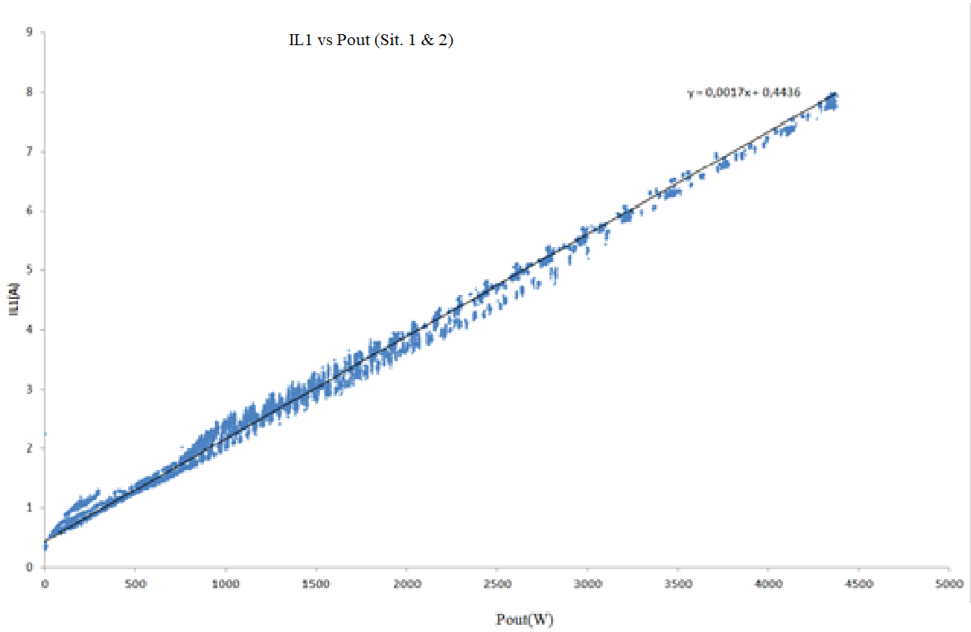


Fig. K.1: IL1 vs Pout

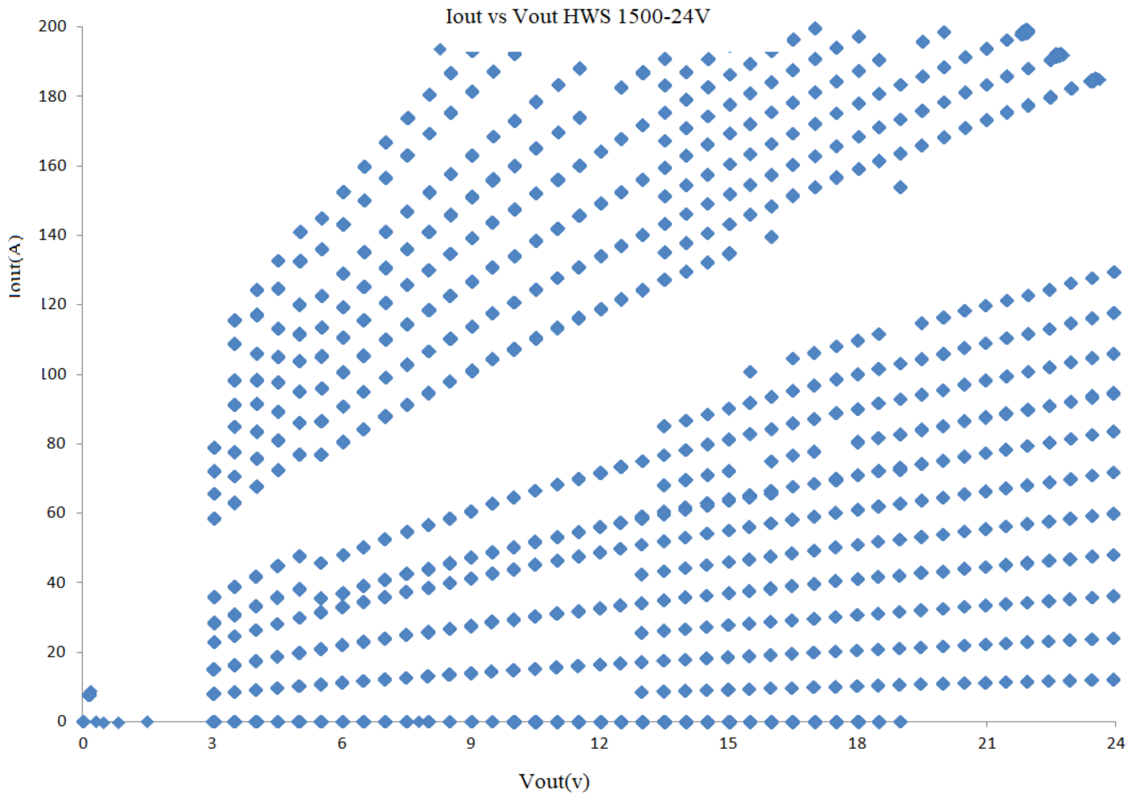


Fig. K.2: Iout vs Vout

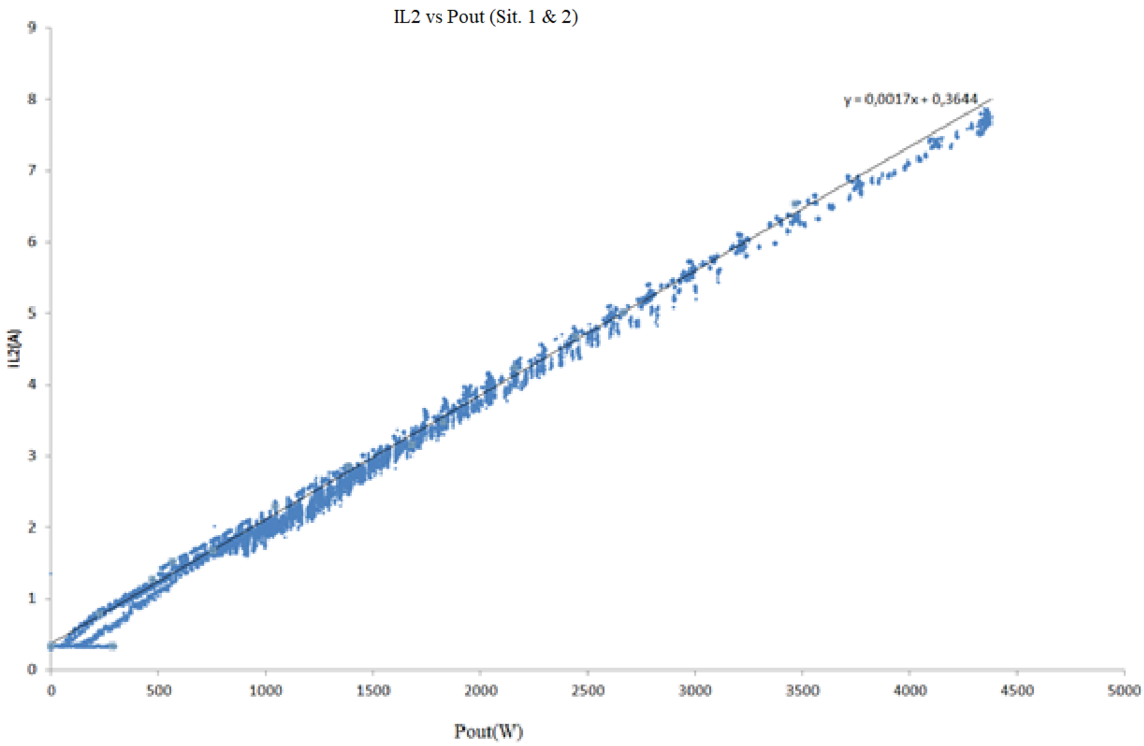


Fig. K.3: IL2 vs Pout

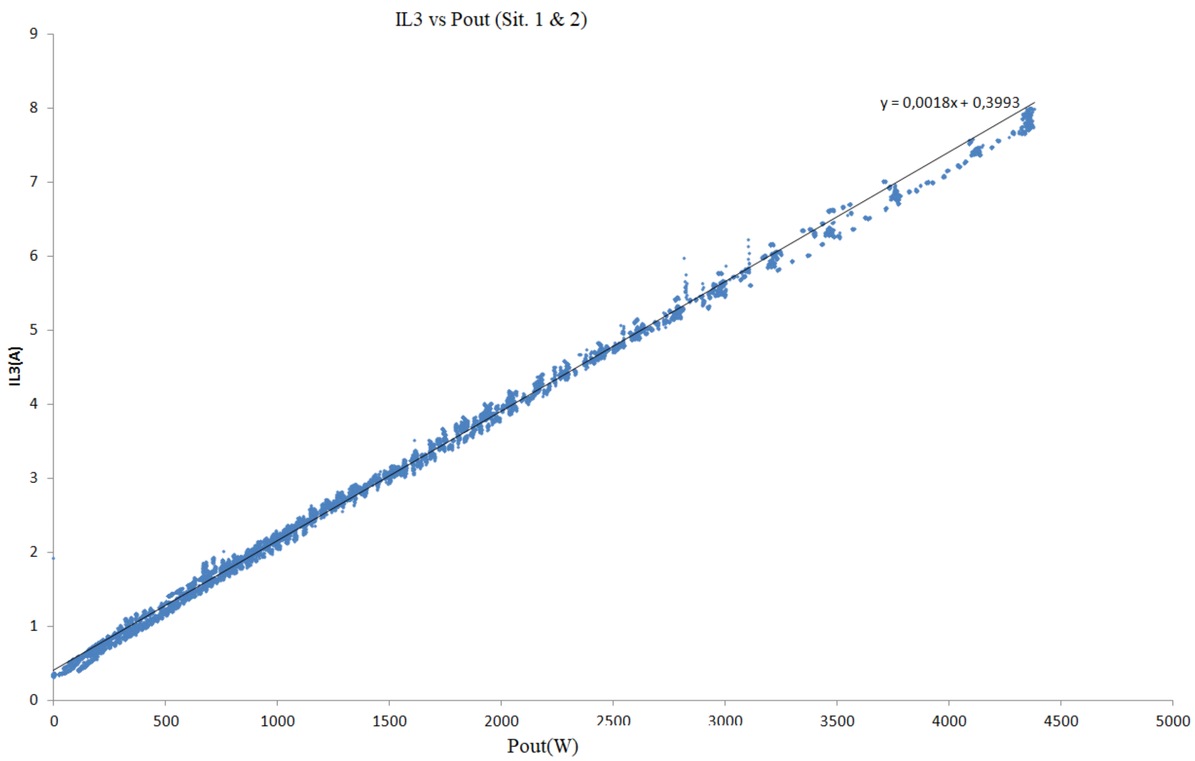


Fig. K.4: IL3 vs Pout

K.2: Test 5

- Some results *(HWS 1000-15)*

Output_Voltage[V]	Output_Current [A]	Output_Current_Rn(A)	Total output current	V L1_L2= (VAC)	V L2_L23 (VAC)	IL1_N= (A)
14,967128	9,3145	-0,025711	9,288788	403711,52	403711,52	695,16208
14,96854	9,402084	0,035629	9,437714	403501,44	403501,44	700,22784
14,966986	9,322282	-0,053024	9,269258	403520,8	403520,8	697,50264
14,967152	9,331132	-0,026779	9,304352	403663,32	403663,32	702,18576
14,968404	9,392472	0,016556	9,409028	403544,64	403544,64	703,66568
14,968246	9,392472	0,025406	9,417878	403538,96	403536,44	697,76704
14,969038	9,401016	0,033951	9,434968	403193,28	403193,28	694,14704
14,969038	9,427262	0,069351	9,496614	403322,92	403322,92	697,9276
14,969976	9,444656	0,077896	9,522552	403189,88	403173,52	698,21616
14,967028	9,312172	-0,054283	9,25789	403315,64	403315,64	698,9264
14,968286	9,338722	-0,019188	9,319534	403385,64	403385,64	706,57272
14,967808	9,338722	-0,028038	9,310684	403463,4	403463,4	693,78952
14,968286	9,364662	-0,010338	9,354324	403173,52	403173,52	700,66184
14,968752	9,382362	0,032997	9,41536	403152,48	403152,48	698,54416
14,966712	9,399758	0,032997	9,432756	403286,76	403286,76	699,28064

14,96907	9,417152	0,041847	9,459	403351,2	403338,2	691,99824
14,961996	18,646888	-0,089073	18,557816	403395,08	403395,08	1006,3196
14,965142	18,733558	0,024452	18,75801	403223,8	403223,8	1005,2036
14,965142	18,759804	0,050392	18,810196	403137,6	403137,6	1006,0874
14,964516	18,768654	0,085793	18,854446	403101,88	403101,88	1009,2758
14,962448	18,621826	-0,04364	18,578186	403416,52	403416,52	1006,3536
14,962914	18,639222	-0,04364	18,595582	403462,64	403462,64	1008,8946
14,9637	18,656616	-0,00885	18,647766	403310,76	403310,76	1005,0544
14,962132	18,648072	-0,00885	18,639222	403072,12	403072,12	1007,011
14,964172	18,717346	0,0177	18,735046	402990,88	402990,88	1004,975
14,966374	18,682556	0,026245	18,708802	403167,32	403167,32	1003,1228
14,964956	18,699952	0,061035	18,760986	403175,12	403175,12	1007,0872
14,967308	18,717346	0,069885	18,787232	402836,6	402827,52	1003,6502
14,965112	18,699952	0,07843	18,778382	402379,16	402379,16	1006,3116
14,965112	18,734742	0,095825	18,830566	402372,68	402372,68	1007,187
14,959194	18,568458	-0,088463	18,479996	402648,16	402648,16	1006,2626
14,941904	27,629432	-0,193138	27,436294	402438,68	402438,68	1284,4404
14,943478	27,664528	-0,131798	27,53273	402610,2	402526,72	1280,9152
14,942694	27,724952	-0,079613	27,64534	402630,08	402630,08	1288,3214
14,941436	27,750892	-0,053368	27,697526	402060,56	402060,56	1287,947
14,942848	27,750892	-0,035667	27,715226	402331,28	402331,28	1282,0322
14,944112	27,811622	-0,018272	27,79335	403906,92	403906,92	1283,8832
14,945518	27,837562	0,007668	27,84523	403681,52	403681,52	1293,498
14,945208	27,846108	0,025063	27,87117	403640	403640	1289,8246
14,945996	27,854958	0,042763	27,89772	403763,92	403763,92	1282,1834
14,943342	27,761498	-0,051308	27,71019	403834,32	403834,32	1289,31
14,943814	27,778892	-0,033913	27,74498	403715,08	403715,08	1285,6824
14,944604	27,770042	-0,007668	27,762374	403502,8	403498,16	1291,3292
14,942562	27,839318	0,018272	27,85759	403778,4	403778,4	1283,2596
14,943502	27,813378	0,018272	27,83165	404108,76	404108,76	1283,6628
14,94193	27,821922	0,018272	27,840194	404090,08	404090,08	1285,5226
14,944916	36,867028	-0,121193	36,745836	403488,56	403488,56	1250,2258
14,94303	36,945152	-0,060158	36,884996	403545,44	403545,44	1253,5138
14,945388	36,971396	-0,007668	36,963728	403445,36	403445,36	1261,275
14,950884	36,945152	0,009727	36,95488	403510,92	403417,44	1219,7046
14,947112	36,945152	0,044823	36,989976	403425	403425	1232,1692

Table K.2: Some results of test 5

- *Graphs of test 5*

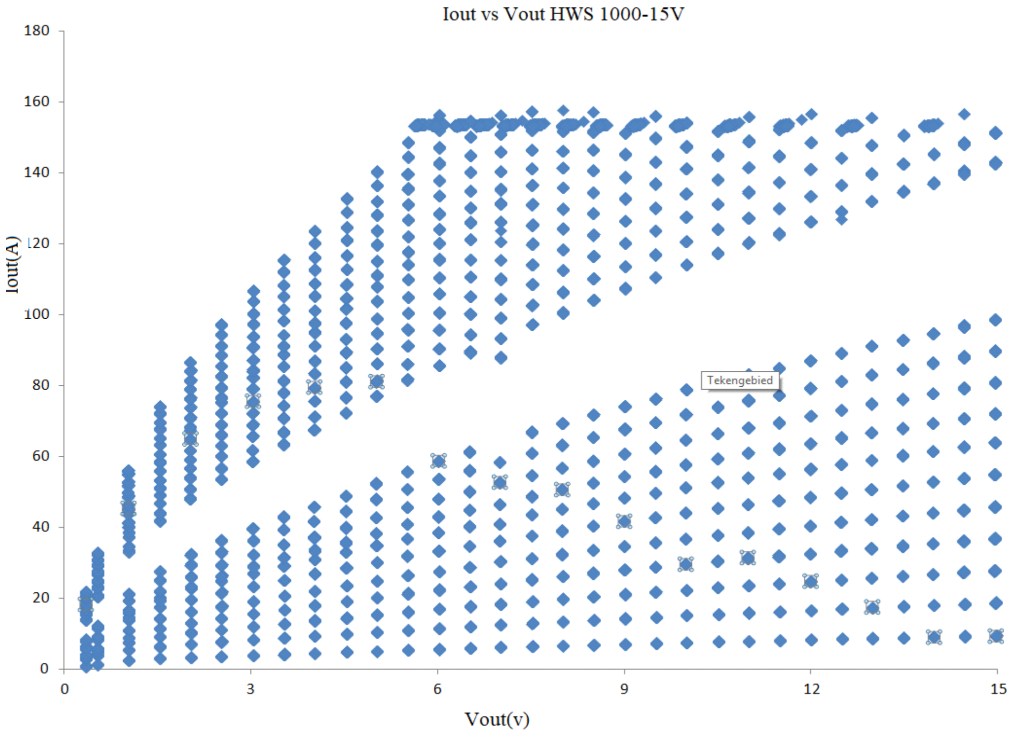


Fig. K.5: Iout vs Vout

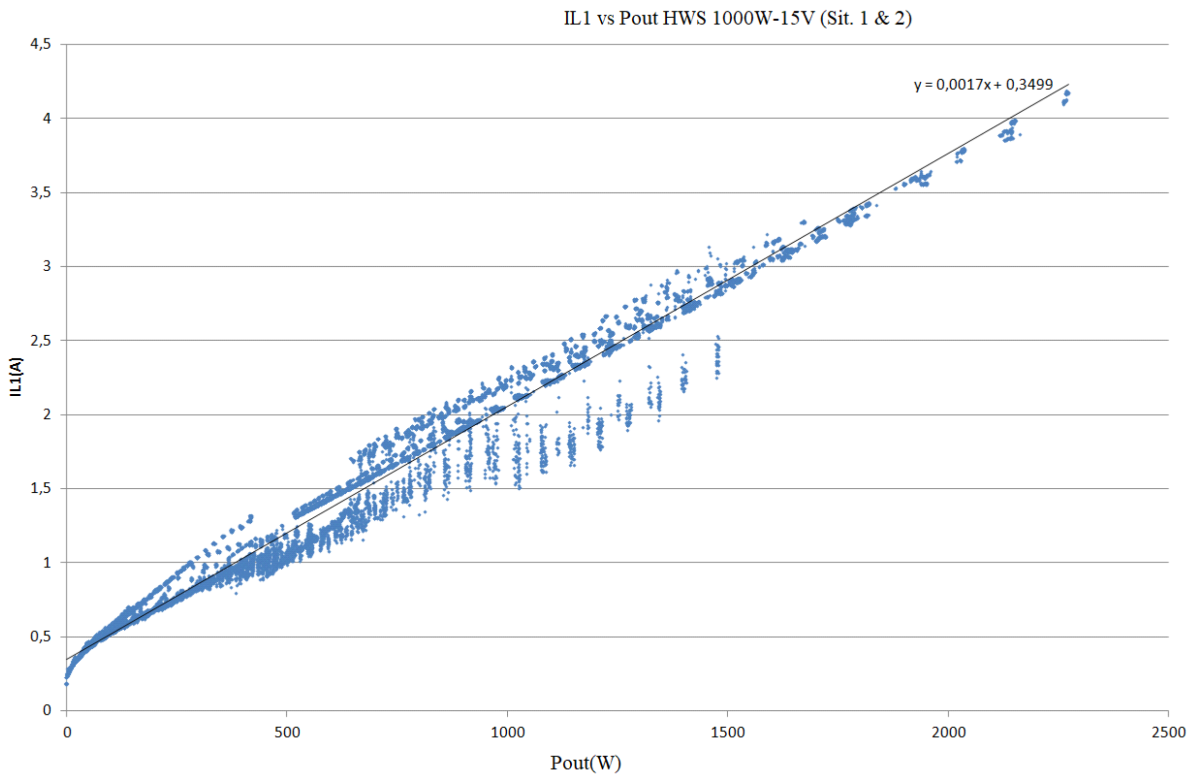


Fig. K.6: IL1 vs Pout

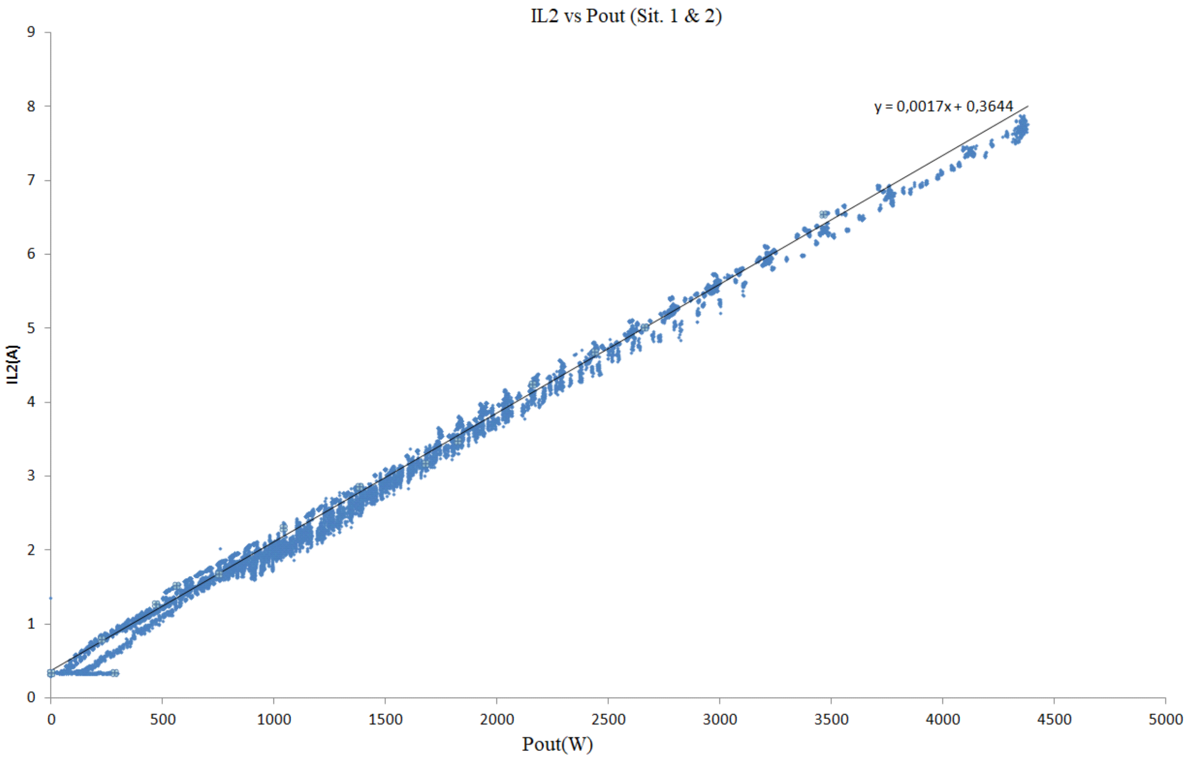


Fig.K.7: IL2 vs Pout

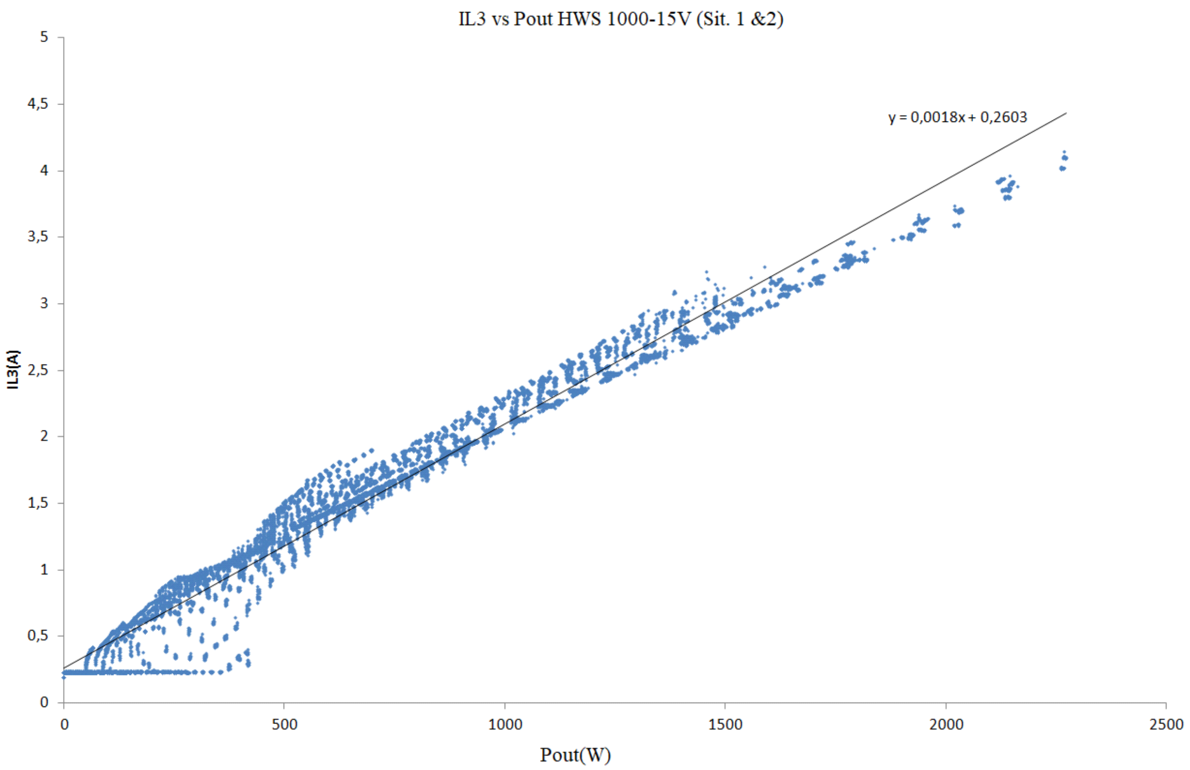


Fig. K.8: IL3 vs Pout

k.3: Prototype ICCP test

- *Some results*

Pout pri(W)	Output_Voltage[V]	Output_Current[A]	Output_Voltage_3diodes(V)	Output_Current_3diodes(A)
291,4907331	23,799712	12,247658	14,81511082	140,78984
293,1943908	23,80417	12,316934	14,82040803	140,84018
293,8274761	23,804848	12,343178	14,82397317	140,87406
294,6138093	23,801468	12,377968	14,82750464	140,90762
290,8762286	23,802248	12,220536	14,81219178	140,7621
291,7108776	23,802784	12,255326	14,81219178	140,7621
291,9258502	23,80373	12,26387	14,81395751	140,77888
291,9241823	23,803594	12,26387	14,8148246	140,78712
292,5406479	23,80292	12,290116	14,8148246	140,78712
292,9695926	23,804132	12,30751	14,81835817	140,8207
292,9695926	23,804132	12,30751	14,82099099	140,84572
294,218534	23,804674	12,359696	14,82012391	140,83748
294,0151469	23,804674	12,351152	14,82275673	140,8625
294,2152463	23,804408	12,359696	14,82365748	140,87106
291,5615754	23,802752	12,24907	14,81114791	140,75218
570,8248024	23,798386	23,985862	14,80816784	140,72386
572,2764748	23,798652	24,046592	14,81256639	140,76566
572,8817878	23,79785	24,072838	14,82049852	140,84104
573,3248768	23,79906	24,090232	14,82049852	140,84104
569,4387523	23,797408	23,928604	14,80374614	140,68184
569,0248201	23,797408	23,91121	14,80287905	140,6736
570,4563303	23,79714	23,971634	14,80551187	140,69862
570,3688818	23,793492	23,971634	14,81081118	140,74898
570,4302492	23,796052	23,971634	14,81257692	140,76576
570,2108329	23,795382	23,963088	14,813444	140,774
572,7358831	23,797408	24,067154	14,81257692	140,76576
572,3088204	23,796864	24,049758	14,813444	140,774
573,3540129	23,79714	24,0934	14,81874331	140,82436
573,7679403	23,79714	24,110794	14,81784466	140,81582
573,7385252	23,79592	24,110794	14,81697757	140,80758
858,5325434	23,796596	36,077956	14,7984805	140,6318
860,2960189	23,799976	36,146928	14,80904545	140,7322
860,8350398	23,79781	36,172868	14,80904545	140,7322

861,6137293	23,802268	36,198808	14,81167826	140,75722
858,5139158	23,796734	36,076964	14,79808694	140,62806
859,5451711	23,796734	36,1203	14,80338625	140,67842
859,4916408	23,795252	36,1203	14,80071976	140,65308
859,5549958	23,797006	36,1203	14,80338625	140,67842
860,3924862	23,79727	36,155092	14,80865189	140,72846
860,4903942	23,799978	36,155092	14,80778481	140,72022
861,2278766	23,797678	36,189576	14,80955054	140,737
860,3431896	23,801734	36,14624	14,81218336	140,76202
861,3011967	23,799704	36,189576	14,81218336	140,76202
861,5242331	23,800248	36,19812	14,8139512	140,77882
861,2375754	23,797946	36,189576	14,81481828	140,78706
1134,482993	23,801734	47,66388	14,79721986	140,61982
1136,072809	23,80065	47,732848	14,80601907	140,70344
1135,7635	23,79417	47,732848	14,80865189	140,72846
1136,231093	23,799704	47,741396	14,80955054	140,737
1135,700913	23,79727	47,724	14,81041763	140,74524

Table K.3: Some results of prototype ICCP test

- *Graphs of Prototype ICCP test*

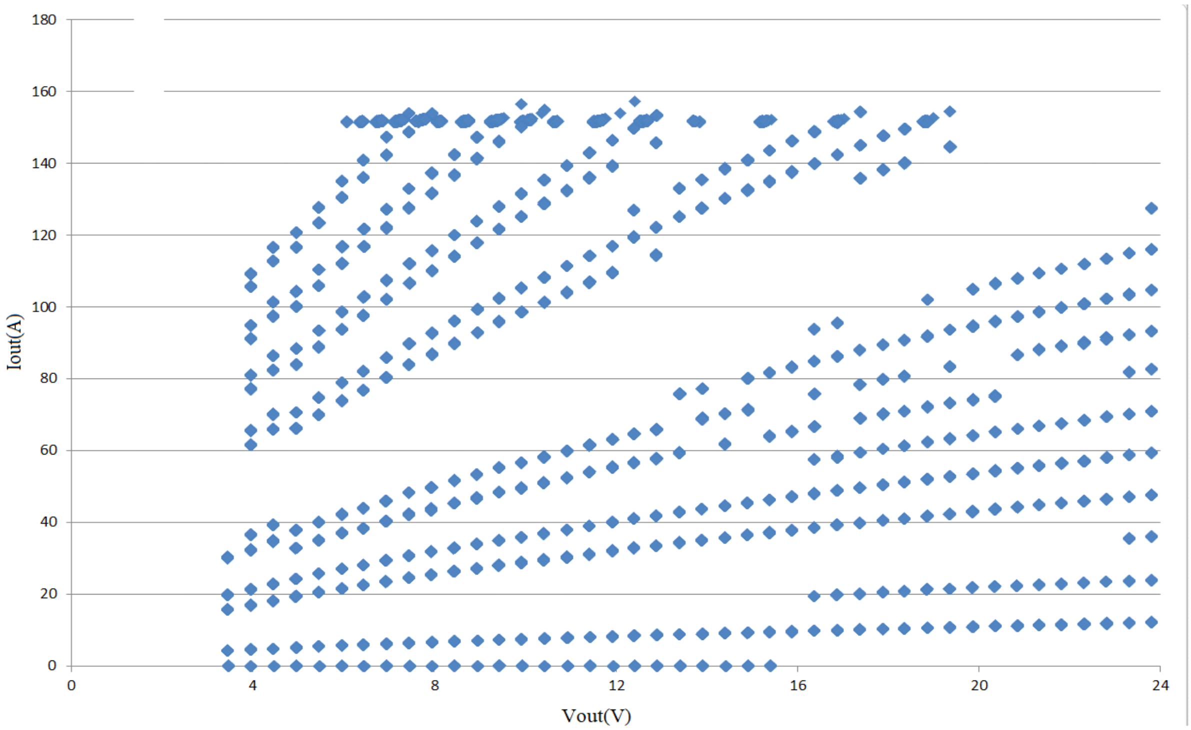


Fig. K.9: Iout vs Vout

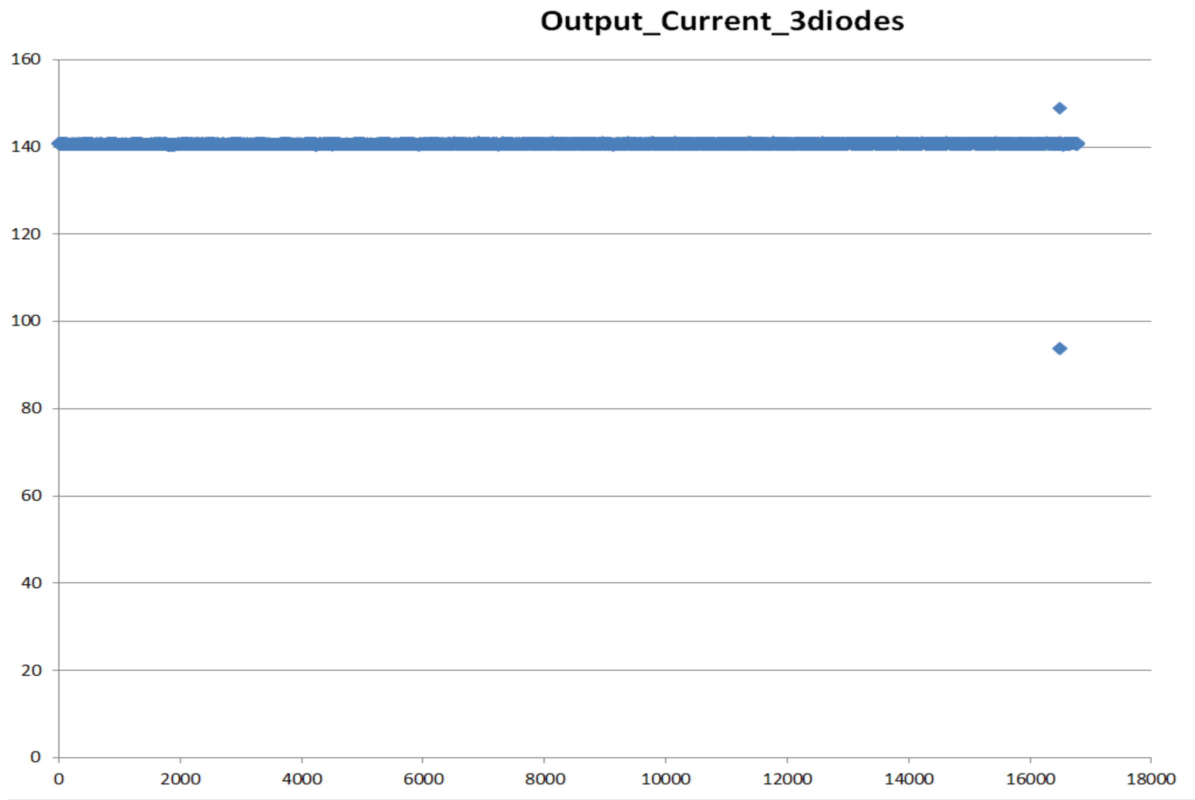


Fig. K.10: Iout vs number of samples