MASTER

Harmonic modelling of solar inverters and their interaction with the distribution grid

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2. Abstract

Increased penetration of power electronic devices such as computers, inverters for distributed generators and lighting equipment, have raised concerns about their impact on power quality aspects in the low voltage grid, such as voltage level and harmonic distortion. Excessive harmonic distortion has been reported in large scale solar plants and similar problems should be prevented in the future. In this report, a model for the harmonic interaction between the grid and power electronic devices is introduced. Through extensive measurements the model is validated for several types of commercially available inverters of different power rating and topology. The measurement strategy, setup, interpretation and results are discussed extensively in this report.
3. Summary

In the last two decades, the number of power electronic devices in the low voltage distribution grid has increased rapidly. Power electronics are mainly used to convert electrical energy from one voltage level to another or from AC to DC and vice versa. Examples of power electronic devices are energy saving lamps, computers and inverters. Inverters are used to feed the energy from distributed generators such as renewable energy sources into the grid. The increasing number of power electronic devices has raised concerns about their impact on power quality aspects, such as voltage level and harmonic distortion. Harmonic distortion is caused by nonlinear loads of which power electronics form the major part. They inject currents into the grid that have a frequency equal to a multiple of the 50Hz net frequency. These harmonic currents induce harmonic voltages in the grid impedance and consequently the grid voltage is distorted. Harmonic voltages can cause overloading of electric motors, transformers and the neutral conductor in cables. Harmonic distortion can also lead to malfunction of sensitive equipment.

Harmonic currents injected by power electronics depend on the harmonic distortion in the grid. This interaction can lead to amplification of harmonic voltages. Devices or groups of devices can form a resonant circuit with cable or transformer inductances. The interaction between power electronics and the distribution grid can be simulated with circuit simulation software. However, this method is not suitable for distribution grids where the number of devices is large and there is no detailed information about their circuit design.

In [1] a model has been proposed that describes the harmonic interaction between the distribution grid and power electronic devices using standard grid components only. It consists of a current source and an admittance. The current source models the harmonic current generated by the device in an undistorted grid and the admittance models the influence of the harmonic grid voltage. The admittance is generally replaced by a parallel conductance and capacitor. The model consists of linear components, and consequently the relation between harmonic grid voltage and inverter current should be linear as well. Voltages and currents at each harmonic frequency are modelled by a separate circuit and the component values can be different for each harmonic. This implies that the \( n^{th} \) harmonic voltage only influences the \( n^{th} \) harmonic current. In the report this is called frequency decoupling. Power electronic devices can operate at different power levels. This is especially the case for inverters as the power generated by the distributed generator can change over time significantly. The model assumes that the harmonic current is independent of the operating power. When component values are expressed in per-Watt a proportional relation is assumed.

When the model is used in combination with a model for the distribution grid, grid effects such as resonances can be predicted. The model is also very suitable to model groups of loads. As such, a model for a typical household or office building could be constructed for use in grid simulation.

The goal of the research described in this report is to validate the proposed harmonic model for solar inverters. Solar inverters are used to feed the energy from solar generators into the distribution grid. Over the years, several topologies (principal design of a power electronic converter) have been developed. Apart from inverter design, different system concepts for solar plants have been introduced. New topologies and system concepts try to reduce cost and improve system efficiency. An overview is presented in the report. Several large scale solar plants have been constructed in the Netherlands and more are planned in the near future. In modern large scale solar plants, high numbers of solar inverters are connected in parallel and measurements have shown that excessive harmonic distortion can occur. These observations have increased the interest in the mechanisms that lie at the basis of harmonic interaction between power electronic devices and the distribution grid.
To validate the model, a measurement strategy was worked out and a measurement setup was constructed. The setup consists of the solar inverter under test, a grid simulator, a photovoltaic simulator, an oscilloscope and a PC. The grid simulator can generate a wide range of grid conditions, including user defined harmonic distortion. The photovoltaic simulator emulates an array of solar generators up to 2.5kW. It feeds the inverter and operates it at a stable and adjustable power. An oscilloscope records voltage and current at the point of connection between the inverter and the grid simulator to determine the harmonic voltage and current distortion. The setup is controlled from a PC and Matlab-based software governs the automated measurement process. The measurement strategy consists of a range of measurements where a harmonic voltage is added to an undistorted grid. Throughout successive measurements, the amplitude and phase of the harmonic are changed. For each setting, the harmonic current distortion is determined. This process is repeated for other harmonics. Between 40 to 120 measurements per harmonic are performed. From the results, model properties are validated and values of model components are determined.

Several inverters of different power rating and topology have been tested and the measurement results are presented and discussed. The general conclusion is that the model describes the harmonic interaction between the grid and the inverter rather well. How accurate the model can predict the harmonic current depends on two factors. The first is the error introduced by assuming a linear relation between harmonic voltage and current. This error is generally within 0.5% of the fundamental. The second is how the harmonic current is affected by other harmonic voltages. The error introduced depends on the amplitude of the harmonic voltage and therefore it is not as straightforward to quantify. For most inverters, the influence is small, but for some inverters it is significant, seriously affecting the accuracy of the model. For most inverters, the model is not valid for even harmonics. When it is valid, model parameters of even harmonics are clearly different from those of odd harmonics. For all inverters, the value of the capacitor in the model is constant for all frequencies. For inverters of higher power rating, the capacitor is larger. The value of the conductance depends on the frequency and can be positive, negative or both. There is no clear relation between the value of the conductance and the power rating of the converter. Model parameters are not independent of the operating power. The capacitor decreases by approximately 15% when the operating power is decreased by 50%. The conductance generally increases, but there is no clear relation to the power level. When two devices are connected in parallel, component values can be added.

In future experiments more inverters can be tested to find relations between model components and inverter topology. The inverters can also be tested at more different power levels to study the relation between model components and operating power in more detail. The grid voltage can be distorted by a combination of harmonics to study the error introduced by cross-harmonic influence more precisely. Small grids of inverters and cables can be constructed to see which components can be neglected and which not. To test more inverters at the same time the hardware photovoltaic simulator has to be extended. An extensive field test on a larger photovoltaic plant gives an opportunity to test the model in a real setup. The measurement setup can be easily adapted to validate the model for other power electronic devices.
4. Introduction

Increased penetration of power electronic devices in the distribution grid has raised concerns about their impact on power quality and losses. 3rd harmonic currents from computers, copiers, energy saving lamps etc. increase losses in the neutral conductor of cables and in distribution transformers. In domestic areas with high penetration of photovoltaic generators, the voltage level at the end of distribution feeders can vary significantly due to changes in generated power.

In general, the influence of harmonic currents generated by power electronic devices on the voltage distortion in the distribution grid is low, because the impedance in the Dutch grid is low. However, harmonic interaction between grid harmonics and large groups of power electronic devices can increase the distortion. Resonances between grid inductance and capacitors in devices can also amplify harmonic distortion. Problems with harmonic distortion are most likely to occur in grids with very high penetration of power electronic devices and little damping. Very high harmonic distortion has already been reported in a large scale photovoltaic plant in The Netherlands [10]. To prevent similar problems in the future, harmonic models of the grid and the devices are necessary. Currently, they are not available.

TU/e, ECN, Continuon and Kema have done research on this topic which has resulted in models for passive network components such as transformers and cables and a proposed model for power electronic components. Several devices such as inverters, TV’s, computers etc. have been tested and some preliminary results have been published. Now, further research is necessary to validate the models in more detail.

4.1 Project goals

The aim of the research described in this report is to validate the proposed model for several types of commercially available solar inverters. This includes several research questions such as

- How accurate can the model predict harmonic currents generated by the inverter?
- If so, are there differences between topologies of inverters?
- Is the model scaleable for inverters of different power?
- Can groups of inverters be combined into one model?

4.2 Project tasks

To answer these questions, several tasks have been performed

- Select and order several commercially available solar inverters of different power and topology.
- Design and build a flexible test setup that can be used to perform harmonic measurements on solar inverters.
- Carry out experiments needed to answer the research questions.
5. Report outline

This section summarises the contents of the coming chapters and appendices.

Chapter 6, Harmonic distortion in the distribution grid, gives a short overview of what harmonic distortion is, what it is caused by and why it should be prevented. The problems of modelling power electronics and the need for new models is explained.

Chapter 7, Complex Conductance Model, gives a detailed description of the proposed harmonic model for power electronics and describes how it can be used in grid simulations.

Chapter 8, The photovoltaic plant, is an introduction into solar generators and inverters. The operation, construction and electrical characteristics of solar cells are discussed. Additionally, the basic design and several common inverter topologies and total system concepts are presented.

Chapter 9, Harmonic distortion from self commutated solar inverters, discusses the origins of harmonic distortion for self commutated solar inverters specifically. An example of a recorded waveform and the influence of harmonic voltages in the grid are discussed.

Chapter 10, Measurement strategy and setup, discusses the measurement strategy and the measurement setup to validate the proposed model.

Chapter 11, Measurement results, presents a summary and a discussion of the results of all measurements carried out. At the beginning of the chapter, various figures and quantities are discussed.

Chapter 12, Conclusions and recommendations, draws conclusions on the obtained results and gives recommendations on future research.

Appendix A, Experiments and results, gives details on the inverters and the conditions under which they have been tested. Further, it contains detailed results of measurements presented in graphical form.

Appendix B, Measurement setup and automation, describes the construction of the PV simulator and the calculation of harmonic distortion. A step-by-step discussion on how a measurement is performed is added; from definition, to execution and processing. Details on file formats and syntax of the most important Matlab functions can be found.
6. Harmonic distortion in the distribution grid

What causes harmonic distortion in the distribution grid and why is it a matter of concern? Why is it difficult to model harmonic distortion? This section deals with these topics.

6.1 Sources of harmonic distortion

Harmonic currents are generated by non-linear loads. Examples of non-linear loads are electrical machines, arc furnaces, lighting equipment, transformers and power electronic devices such as motor drives, power supplies, inverters etc. In essence, a non-linear load draws a non-sinusoidal current when a sinusoidal voltage is applied to its terminals. Fourier's theorem states that any periodic waveform can be described as a sum of sinusoids with certain frequency, amplitude and phase. The non-linear load thus adds current components with higher frequency to the fundamental current. Depending on the type of distortion only some frequencies occur. When a frequency is an integer multiple of the fundamental frequency it is called a harmonic frequency (hence the term harmonic distortion); all other frequencies are called inter harmonics. Most common electric components do not produce inter harmonics (except for example arc furnaces and welding equipment). Frequency components below the fundamental are called sub harmonics. They are caused by time varying loads (both linear and non-linear). [2] gives a nice overview of Fourier's theorem and various sources of harmonic distortion.

Harmonic currents induce a voltage in the grid impedance that is added to the grid voltage, thereby distorting the grid voltage. The grid impedance is usually small and therefore the voltage distortion is low. For example, if a group of devices has a fundamental current that causes a 5% voltage change and the 3rd harmonic current is 5%, the voltage induced by the harmonic current is only 0.25%. A resonance in the network can amplify the harmonic voltage significantly.

6.2 Effects of harmonics

Harmonic distortion can lead to overloading of electric motors, transformers and neutral conductors of cables. Equipment malfunction is a relatively new phenomenon. Whereas power electronics generate harmonic distortion, they are also susceptible to it. Certain distortions can lead to sudden malfunction of devices. Malfunction of solar inverters due to harmonic distortion is reported in [II] and has been observed in the measurements presented in chapter II of this report.

6.3 Modelling

In order to prevent problems caused by harmonics in distribution grids, a simulation tool is necessary. There are several simulation packages that focus on load flow and transient simulation, but they lack models for harmonic distortion.

A harmonic model describes the electric properties of a component for all harmonic frequencies. Linear (or close-to-linear) components like cables, transformers, classis light bulbs, cooking furnaces etc. can be modelled by a frequency dependant impedance. In [2] an impedance model is derived for a distribution cable and a power transformer. A linear system can be modelled as the sum of independent linear subsystems for each harmonic frequency. The systems are independent because an \( n^{th} \) harmonic voltage only influences the \( n^{th} \) harmonic current. Non-linear systems cannot be modelled like that, because the subsystems are not independent. In a non-linear system, the \( n^{th} \) harmonic can also influence other current harmonics.
The IEC 61000-3-2 standard defines the maximum harmonic current for devices. The harmonic current is to be measured when the device is connected to an undistorted voltage. Standard EN50160 and the Dutch national grid code define the maximum voltage distortion in the grid and the devices should still operate under those conditions. However, the influence of harmonic voltages in the grid on the harmonic currents generated by the device is also very important. A device could attenuate or amplify certain harmonics or resonate with the grid at harmonic frequencies. For power electronics, this interaction is not straightforward. As there is not standard that defines this relation, little research has been done into this field.

Simulation of power electronics is usually done by entering the entire or a simplified version of the circuit and control loops in an electronic simulator. In this way, every possible grid situation can be simulated. One could incorporate these simulations in a grid simulation tool, but there are two major disadvantages. First of all, one would have to know the exact circuit design of all power electronic components in the grid and enter them all into the simulation. Even if this detailed information was available it would take too much time. Secondly, the switching frequency of power electronics (10 - 500 kHz) is very high compared to the grid frequency. To obtain a good simulation the time step would have to be decreased, thereby increasing the simulation time dramatically.

Given the prohibitions of detailed circuit simulation in grid simulation one would need a model for power electronics that uses only a small amount of standard grid components already available in most grid simulation packages. The model presented in the next chapter attempts to do just that.

6.4 Conclusion

Non-linear loads like power electronics induce harmonic currents in the distribution grid. Harmonics lead to higher losses, overloading, and malfunction of sensitive devices. Increased penetration of power electronics can lead to excessive harmonic distortion in distribution grids and therefore a model is necessary that can predict harmonic levels and resonances. Power electronics can be simulated using detailed circuit simulation, but this is impractical as distribution grids have a large amount of connected devices and their exact circuit design is unknown. A simple model using a small amount of standard grid components is required.
7. Complex conductance model

In the previous section, the need for a simple harmonic model for power electronic devices was demonstrated. In [1] such a model has been proposed. It is referred to as the complex conductance model.

Figure 7-1 shows the model in combination with the distribution grid.

\[ \begin{align*}
\text{Grid} & \quad Z(n) = R(n) + jX(n) \\
\text{Non-linear load} & \quad I(n) \\
U_{\text{grid}}(n) & \quad V(n) \quad Y(n) = G(n) + jB(n) \\
I_y(n) & \quad I_0(n) \quad I(n)
\end{align*} \]

Figure 7-1. Proposed model for harmonic behaviour of power electronics. The left part represents the distribution grid and the right part a power electronic device. Model parameters depend on the harmonic frequency.

\[ \begin{align*}
U_{\text{grid}} &= \text{harmonic grid voltage,} \\
Z &= \text{grid impedance,} \\
V(n) &= \text{terminal harmonic voltage,} \\
I(n) &= \text{terminal harmonic current,} \\
Y &= \text{admittance,} \\
I_y(n) &= \text{harmonic current through admittance,} \\
I_0 &= \text{harmonic current source,} \\
n &= \text{number of harmonic.}
\end{align*} \]

The voltage source and the impedance on the left represent the distribution grid. The admittance and current source represent the power electronic device. The system consists of only linear components and as it was described in chapter 6, linear systems can then be split up into a separate sub systems for each harmonic frequency. Each sub system has the same components, but with different component values. This is indicated in the model by the \( n \) in brackets. \( U_{\text{grid}}(n) \) is thus the \( n \)th harmonic grid voltage, \( I(n) \) the \( n \)th harmonic terminal current and \( Z(n) \) the grid impedance for the \( n \)th harmonic frequency.

\( I_0 \) represents the harmonic current distortion generated by the power electronic device when the terminal voltage is undistorted. \( V(n) \) is then zero for all \( n \neq 1 \) and consequently \( I(n) \) is equal \( I_0(n) \). Admittance \( Y \) represents the influence of a harmonic voltage at the terminals of the device. \( V(n) \) induces a current \( I_y \) through \( Y \). \( I(n) \) is the sum of \( I_0(n) \) and \( I_y(n) \). \( G \) (the real part of \( Y \)) and \( B \) (the imaginary part of \( Y \)) can be positive or negative allowing \( I_y(n) \) to be shifted over \([-\pi, \pi]\) with respect to \( V(n) \).

7.1 Model properties

The next section discusses the properties of this model in detail. These properties are a guideline for model validation further on in the report.

**Linearity**

The model assumes a linear relation between harmonic voltage and current. In figure 7-2-a an example of voltage and current phasors for a certain harmonic frequency are drawn. Terminal current \( I \) is equal to the sum of \( I_0 \) and \( I_y \). \( I_0 \) is constant and \( I_y = V \cdot Y \). In this example the real part of \( Y \) is negative and the imaginary part is positive. In figure 7-2-a the amplitude of the terminal harmonic voltage is changed. Terminal harmonic current \( I \) then moves along a straight
line. In figure 7-2-b, the phase of $V$ is changed. I then follows a circle and $I_0$ is the centre of the circle.

![Diagram showing linear relation between terminal voltage and current](image)

**Figure 7-2. Illustration of linear relation between terminal voltage and current.** $I_0$ is constant and $I_y = V \cdot Y$. When the amplitude of $V$ is changed, $I$ follows a line; when the phase angle of $V$ is changed, $I$ follows a circle.

**Frequency decoupling**

As mentioned before, linear systems can be seen as the sum of separate sub systems at different frequencies. In other words, an $n^{th}$ harmonic voltage only induces a change in the $n^{th}$ harmonic current. In principle, this does not hold for non-linear loads as was pointed out in chapter 6. It is however observed that certain power electronic devices behave like that by approximation. As we want to do a good approximation of the harmonic current, a small frequency coupling is acceptable.

**Influence of power level**

Power electronic devices can operate at different power levels. This is certainly the case for solar inverters as their power depends on the irradiation of the connected solar panels. The model assumes that harmonic currents are independent of the power level. When there is an influence and the relation is proportional one could define the component values in per-Watt.

The model is validated further on in the report on the basis of measurements. In the chapter 9 some preliminary remarks are made on whether the above properties could be valid for solar inverters.

### 7.2 G and C instead of Y

In chapter 12, measurement results, admittance $Y$ is represented by a parallel conductance ($G$) and capacitor ($Y$) (see figure 7-3). $G$ represents the real part of the $Y$ and $C$ the imaginary part ($G = \text{real}(Y), C = \text{imag}(Y)/2\pi f$). This is done because it is easier for discussion. Note however that as $Y$ is defined for one frequency only, it can be represented by any passive circuit. The advantage of using a parallel conductance and capacitance is that they, like $Y$, can be added when put in parallel. This is convenient when several parallel devices are modelled.

### 7.3 System transfer and resonances

Let's assume for a moment that the model indeed describes the harmonic current generated by the device with reasonable accuracy. It is then very convenient to be used in grid simulations.
Figure 7-4-a shows a model of a grid where several linear and power electronic devices are connected in parallel along a cable.

![Figure 7-3. Y is represented by a parallel conductance G and capacitance C.](image)

Figure 7-4. a) Distribution grid where two power electronic loads and a linear load are connected along a cable. b) If the cable impedance can be neglected, several loads can be combined in one model by adding the components.

Because the model uses linear components, standard analytical calculation methods can be used. The system transfer can be calculated and series or parallel resonances can be determined. One should however bear in mind that component values are only valid for a certain frequency. In theory one could thus have more or less resonances than is expected in a circuit with constant component values for all frequencies. Because the power electronic device is an active component, the real part of Y can be negative (like in figure 7-2). The device then feeds energy at harmonic frequency into the circuit instead of dissipating it and this amplifies the harmonic. In grids with a large number of devices and little damping by other devices or long cables the amplification can become very large. A large photovoltaic plant is an example of such a grid.

### 7.4 Modelling a large number of loads

A typical distribution grid may have hundreds of loads and it is generally not known what kind they are exactly. Entering all loads and cable impedances into the simulation is very time consuming. Therefore one would like to model groups of loads in one model. If one assumes that the effect of the cable impedance is small compared to Y, all admittances and current sources can be added combining all models into one. This is illustrated in figure 7-4-b. This way one could compose a model for a typical household or office building or groups of those. These models could than give an indication of the harmonic distortion in a distribution grid. For specific problems the grid can be modelled in more detail.

### 7.5 Conclusion

The complex conductance model models harmonic currents generated by power electronic devices. The model consists of a current source and an admittance whose values can be different for each harmonic frequency. The model assumes a linear relation between harmonic terminal voltage and current, decoupling of systems at different harmonic frequencies and no influence of the actual power level of the device. The model can predict resonances between the device and the grid or among devices. Because the device is active, it could amplify certain harmonic frequencies.
8. The photovoltaic plant

This chapter gives a short overview of which components a grid connected photovoltaic plant consists of and how they operate. First, the operation, construction and electrical characteristics of photovoltaic generators are discussed. Then, the basic operation and several common topologies are treated. Finally, several system concepts are presented.

A typical setup of a grid connected photovoltaic plant is shown in figure 8-1. A DC electric current is generated by a series of photovoltaic generators. An inverter converts the current to AC and feeds the energy into the grid.

![Figure 8-1. A grid connected photovoltaic plant consists of an array of photovoltaic generators and an inverter that feeds the energy into the distribution grid.](image)

8.1 The photovoltaic generator

This chapter shortly summarises the operation of solar cells and how they can be modelled. A more detailed discussion can be found in literature, for example [12].

8.1.1 Operation of a photovoltaic cell

A photovoltaic cell is a semiconductor device that converts energy from light into electric energy. It is a p-n junction, like a diode. The n-area has an excess of electrons in the valence band that can jump to the conduction band with little energy. The p-area has a shortage of electrons in the valence band. This leaves available places called holes. When these materials are placed together, electrons from the n-area diffuse to the p-area where they fill up a hole (recombination). A migrating electron leaves back a hole that can recombine with another electron. As electrons diffuse from the n to the p area, holes diffuse from the p to the n area. The diffusion has two effects. Firstly, around the barrier an area with less excess electrons and holes is created, called the depletion zone. Secondly, as the electrons and holes diffuse, negative charge is moved from n to p area and positive from p to n. This causes an electric field that opposes the diffusion. An equilibrium is established.

When an external voltage is applied over the junction, the diffusion field is either increased or decreased thereby opposing or favouring the transport of charge. Consequently the device only conducts current from the p to the n area (the electrons then go from the n to the p area). This effect is known as the diode effect.

When a photon of high enough energy hits an electron in the valence band of the p-area, it can jump to the conduction band. Here, it can either fall back and recombine with the hole it just left behind or it is drawn to the n-area by the diffusion field. The charge-diffusion equilibrium is disturbed and consequently an electron will pass the barrier the opposite way to restore the balance. If there is a conducting path from the n-area to the p-area, the equilibrium can be restored by transferring charge through the conducting path. When a load is connected in series with the conducting path, a current flows and the energy from the photon is transferred to the load. This is known as the photovoltaic effect. The number of electrons that are lifted to the
Chapter 8. The photovoltaic plant

Conduction band depends on the amount of light (irradiation) that is absorbed and the temperature. Whether the electron flows through the load or over the p-n junction depends on the voltage across the load (and the cell). When the voltage is zero (a short circuit) all charge goes through the load. When the voltage is equal to the junction voltage, all charge moves over the junction. Between those two extremes an equilibrium is established. The current that flows in a short circuit situation is called short circuit current. The voltage across the cell when no load is connected is called open circuit voltage.

The short circuit current and the open circuit voltage depend on the irradiation. When the irradiation decreases, the short circuit current and the open circuit voltage both decrease. The open circuit voltage also depends on the temperature. When the temperature rises, the open circuit voltage decreases. This is shown in figure 8-2-b.

Figure 8-2. Typical characteristic of a photovoltaic cell. (a) Irradiation dependence. (b) Temperature dependence. (images from [12]).

Figure 8-3, shows the characteristic of a photovoltaic cell for certain irradiation and temperature together with the power delivered to the load. The power has a maximum, called the Maximum Power Point (MPP). The voltage at which the MPP occurs is the MPP voltage and the corresponding current is the MPP current. The MPP voltage occurs at approximately 80% of the open circuit voltage, the MPP current is approximately 90% of the short circuit current. Like the open circuit voltage, the MPP voltage depends on the irradiation and the temperature.

Solar cells have a low capacitance over the output terminals. The capacitance is the junction capacitance of the diodes and consequently it depends on the voltage across the cell, the temperature and the irradiation. [4] states a typical value of 1.0uF for a 10kW PV generator. Consequently, the output current adjusts to the voltage across the cell rapidly. This is important for the construction of a photovoltaic simulator, as described in appendix B.1.

Figure 8-3. a) V-I curve of a typical and the power delivered to the load. The power has a maximum called the maximum power point (MPP). (image from [12]) b) Simplified model of a photovoltaic cell connected to a load. Influence of temperature and internal losses are neglected.

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8.1.2 Model of a PV cell

Figure 8-3-b shows a simple model of a photovoltaic cell. It consists of a current source and a diode. The current source represents the short circuit current. It depends on the irradiation of the cell. The p-n junction is modelled by a parallel diode. Temperature dependency and internal losses are not taken into account in this model. The photovoltaic simulator described in appendix B.1 is based on this model.

8.1.3 PV array

To achieve higher output voltage and power, multiple PV cells are connected in series into a PV module. Multiple modules in series form strings. When all cells in the array are physically identical and are irradiated equally, each cell generates the same current and the voltage over the array is distributed equally over all cells. An array of photovoltaic cells can be modelled by placing multiple current sources and diodes in series (see figure 8-5-a). Figure 8-5-b shows the V-I curve for different numbers of cells.

8.1.4 Construction of a photovoltaic cell

In 8-6-a the construction of a photovoltaic cell is shown. p and n doped silicon is fabricated the same way it is done for other semi-conductor devices. A metal cathode and anode are added to conduct current from the device. The cathode is finger-shaped to allow light to reach the silicon. The n-area is thin to absorb as little light as possible. The p-area on the other hand is thicker to maximise light absorption. A non-reflective coating is added on top of the cathode to reduce reflection.
8.1.5 Conclusion
A photovoltaic cell is a semiconductor p-n junction that generates a current when it is irradiated. The current depends on the irradiation and the voltage across the anode and cathode. The power delivered to the load has a maximum (MPP). It occurs at approximately 80% of the open circuit voltage. Approximately 90% of the short circuit current is then delivered to the load. A PV cell is modelled by a current source and a parallel diode. Multiple cells connected in series make a solar module with higher output voltage and power.

![Figure 8-6](image_url)

Figure 8-6. a) Construction of a photovoltaic cell. The cathode is finger-shaped to let light be absorbed by the silicon. Photovoltaic processes are shown schematically by '+' (hole) and '-' (electron) signs.

b) Photo of a commercial cell. It shows the rasterised shape of the cathode. The anti-reflective coating gives the cell a blue colour.

8.2 The photovoltaic inverter

To feed the energy of the photovoltaic generator into the grid, an inverter is needed. For maximum yield, the inverter should have a high efficiency and should operate the solar array in its maximum power point.

The solar inverter fulfils several functions that can be sequenced in a different way depending on its topology. They are:
- Maximum power point tracking
- Boost the input voltage to grid voltage if necessary
- Shape the output voltage to a sinusoid.
- Invert the current to AC

MPP tracking is generally performed by a DC-DC converter. It feeds the energy into an internal DC bus that feeds the other stages of the inverter. This converter is sometimes also used as a boosting element. Another way of boosting the voltage is a transformer, at high or grid frequency. Current inversion is generally performed by a bridge converter.

In the next section, an overview of the most common converter topologies is given.

8.2.1 MPP tracker
The MPP tracker aims to operate the solar panel at maximum power. By controlling a DC-DC converter, the input voltage and current can be regulated. If the input voltage is equal to the MPP voltage, maximum power is delivered to the inverter. As the MPP voltage changes with the irradiation and the temperature of the solar cells, an algorithm is needed to track the MPP voltage.

There are several MPP algorithms, of which two are widely used. The first is a tracking algorithm. By varying the input voltage, the algorithm searches for a point where the gradient of the power curve (dP/dV) is zero. The second type of algorithms measure the open circuit voltage and
Chapter 8. The photovoltaic plant

estimate the MPP voltage at 80%. The latter requires that the current to the inverter is shortly brought to zero to measure the open circuit voltage. It was mentioned before that solar cells have a low capacitance and consequently a high bandwidth. MPP trackers can therefore change the input voltage of the converter quickly to find the MPP voltage. Tracking algorithms use frequencies of over 400 Hz. Algorithms that measure the open circuit voltage interrupt the input current only very shortly.

Commonly used input converter topologies are the buck, boost and buck-boost converter (see figure 8-7). At the input and output, the converters are controlled as voltage sources.

![Buck, boost and buck-boost converter topologies](image)

Figure 8-7. Buck, boost and buck-boost converter topologies are commonly used to adjust the input voltage of a solar inverter. An MPP algorithm finds or estimates the maximum power point of the photovoltaic generator.

8.2.2 Current inversion

Most inverters use a full-bridge topology to invert the current. Figure 8-8 shows a line commutated and self-commutated full bridge. The line commutated bridge converter uses thyristors as switching devices. It is very robust, cheap and has a high efficiency. Its disadvantages are a low power factor (0.6 to 0.7) and the high harmonic content of the output current. Line commutated inverters were used in the past for high power inverters, but because of their bad influence on power quality they are largely replaced by self commutated topologies.

Self commutated inverters use switches that can be fully controlled like GTO’s, IGBT’s and MOSFET’s. There are different switching schemes, but the sinusoidal PWM (pulse width modulation) control is the most common for solar applications. The devices switch at high frequency (10-25kHz) with a sinusoidal distributed duty cycle. The harmonic distortion introduced by the switching ripple lies around multiples of the switching frequency which makes filtering easier. The power factor can be controlled to approach unity. Its drawbacks are less efficiency due to high switching frequency and increased control.

Chapter 9 deals with harmonic distortion from inverters in more detail.

![Full bridge converter topology](image)

Figure 8-8. The full bridge converter topology is a commonly used as inversion stage. Line commutated inverters are robust and cheap but operate at low power factor and require large output filters to reduce harmonic distortion. Self commutated inverters that switch at high frequency are more flexible but require more control electronics.
8.2.3 Voltage boost and isolation

When the voltage from the solar array is lower than the peak line voltage a boosting element is necessary. Line or high frequency transformers are frequently used because they provide isolation between the photovoltaic generator and the net. However, magnetic components are expensive and reduce the overall efficiency of the converter. Transformerless topologies use DC-DC converters with boosting capability. Figure 8-9 shows schematic representations of different topologies.

![Schematic representations of inverter topologies with and without transformer](image)

**Line transformer**

The use of a line transformer allows all active components of the converter to be operated at a voltage below grid level. This reduces cost. All measurement and control is located on the primary side of the transformer which simplifies the design. The main disadvantages are size, weight and cost of the transformer (see figure 8-10).

**High frequency transformer**

The size of the transformer is reduced significantly when a high frequency transformer is used between the input and the final inverting stage. It requires a high frequency inverting stage before and a rectifier stage behind the transformer. If these stages include voltage shaping the main inverting stage can be switched at 50Hz which reduces losses. Increased control and components are a disadvantage of this topology.

**Transformerless topologies**

In recent years, transformerless inverters have gained market share. As they eliminate the use of a transformer, cost is reduced and efficiency increased. Figure 8-10 shows the advantage of transformerless inverters over inverters with a line transformer. There has been a lot of concern whether these topologies are safe because they do not provide galvanic isolation from the net. When an isolated inverter is used, the inputs of the inverter float with respect to the net. Contact to one of the phases will not lead to an electric shock. Transformerless topologies generate a common mode voltage on the DC input terminals. The amplitude and shape of that voltage depend on the topology and switching scheme of the inverter. Contact with one of these leads is hazardous. Photovoltaic cells also have a capacitance to the frame of the module. If the module is touched, the common mode voltage induces a current through that capacitance and the human body to the ground. The capacitance is in the order of 20nF per square meter or approximately 100W installed power [4]. The induced current is not dangerous, but can be unpleasant [3]. An internal earth leakage detector and increased isolation requirements of the solar modules prevent dangerous currents. The earth leakage detector in transformerless inverters can be a problem in the measurement setup. This topic is discussed in more detail in appendix B.1.

**Other**

In recent years, new topologies have been developed. They aim to reduce cost and improve the efficiency at part load thereby increasing overall system efficiency. More on this topic can be found in literature [5, 6, 7].
8.2.4 Conclusion

A photovoltaic inverter feeds the energy generated by a photovoltaic generator into the grid. Four tasks, maximum power point tracking, voltage boosting, current inversion and output current shaping, are distributed over several stages of the converter. Nowadays, most inverters use self-commutated topologies that reduce harmonic distortion and improve the power factor. Topologies with low frequency transformers have been replaced by high frequency transformer topologies to reduce weight and cost. In recent years, transformerless topologies have gained market share. They reduce cost and increase efficiency further but there have been concerns about safety because they don't provide isolation between the grid and the photovoltaic generators.

8.3 Photovoltaic system concepts

Over the years, developments in technology, the search for cost reduction, increased efficiency, flexibility and reliability have lead to several photovoltaic plant system concepts. In the next part, different concepts are presented and shortly discussed.

Central inverter
Strings of solar panels are connected in parallel to a DC voltage bus. One central inverter feeds the energy into the grid. A central inverter is cheap, robust and efficient, but extensive DC wiring increases cost and introduces the risk of sparking. With only one MPP tracker there is no compensation for situations where part of the modules is shaded. Furthermore the system is not very flexible and standardisation is difficult.

Module integrated
The other extreme is module integrated inverters. Each panel (with a power rating of up to 500 W) has its own inverter that feeds directly into the grid. The system is as modular as possible, each panel is operated at its maximum power and no DC wiring is required. Additionally, the system keeps operating if one or more inverters fail. Drawbacks are higher costs per Watt rated power, reduced inverter efficiency and increased service cost.

String inverter
This concept is a trade-off between central and module integrated inverters. Each string of typical several kW’s is connected to its own inverter. System efficiency is higher than with one central inverter, costs per Watt are reduced compared to the module integrated system and service is easier. Requirements for DC wiring are much less. The string concept is popular in domestic PV systems.
Multi string
This concept combines the higher system efficiency of the string concept with the lower cost of a central inverter. Each string of panels has its own MPP tracker that feeds into a DC bus. A central inverter feeds the energy into the grid. A disadvantage is the need for expensive DC wiring.

Team concept
The team concept seeks to improve efficiency at part load. It uses several string inverters in master-slave operation. When the irradiation is low, several slaves are switched off and the strings are connected to the remaining inverters. These inverters are then operated in a region with higher efficiency.

8.3.1 Conclusion
Different PV system concepts have been developed. They are a trade-off between production, installation, and service cost, overall system efficiency, standardisation, flexibility and reliability. Popular system designs are central inverter, module integrated inverter, string inverter, multi-string and team concept.
9. Harmonic distortion from self commutated inverters

All power electronic converters generate harmonic currents. However, the reason why they are generated can differ from device to device. In this section, the fundamental mechanisms that cause harmonic distortion from self commutated inverters are discussed.

9.1 Origin of harmonic distortion

Most modern solar inverters for module integration or string concept are self-commutated. They have an internal sinus generator that is synchronised with the grid frequency. A controller shapes the output current to fit the internal sinus as good as possible. Figure 9-1-a shows a typical current waveform from one of the tested solar inverters. It shows that the waveform is not completely sinusoidal. The fundamental component is indicated by the dashed line. This would be the ideal current shape.

Figure 9-1-b shows the difference between the actual current and the fundamental. It is the sum of all harmonic currents. The high-frequent switching ripple can easily be distinguished. The distortions around the zero-crossing are due to limitations in the PWM control [8]. Figure 9-1-c shows frequency components of the distortion current up to 30kHz. The graph clearly shows the lower harmonics due to the inability of the inverter to shape the current to an undistorted sine wave and the higher switching harmonics. In this report, we focus on the lower part, up to n=50 (2.5kHz). The high-frequency switching harmonics are attenuated by the distribution grid or other devices nearby, so they are less likely to cause any problems.

9.2 Influence of harmonic grid distortion

Figure 9-2 shows an illustration on how harmonic voltages in the grid can affect the harmonic current from the inverter. Figures a, b and c show voltage, inverter current and harmonic content of the inverter current for an undistorted grid voltage. Figures d, e and f show the same signals when the grid voltage is distorted with 4% 3\(^{rd}\) harmonic with phase of 20 degrees and 3% 7\(^{th}\) harmonic with phase of -10 degrees with respect to the fundamental. This distortion was generated by a grid simulator to illustrate the influence of grid distortion, it is not a common distortion in the grid. As a result of the distortion, the amplitude of the 3\(^{rd}\) harmonic current has decreased significantly and the 7\(^{th}\) has increased. Other harmonics remain unchanged. This shows that harmonic grid voltage has influence on the harmonic current generated by the inverter and that voltage harmonics can cancel or increase current harmonics. It also shows that - at least in this case - the influence is limited to the same harmonic, justifying frequency decoupling that is essential for the proposed model.

9.3 Conclusion

Harmonic currents generated by self-commutated inverters have two main origins. High frequency components due to switching ripple and lower frequency components (n<50) due to the inability of the inverter to shape the current to a perfect sinusoid. The higher harmonics are filtered out by the distribution grid and other devices nearby. In this report, the focus is on harmonics up to n=50. Harmonic voltages in the grid can lead to an increase or decrease of harmonic currents from the inverter.
Figure 9.1.
(a) Current of one of the tested solar inverters (solid) and its fundamental (dashed)
b) Distortion current (current - fundamental)
c) Frequency components of distortion current (up to 30kHz)
Figure 9-2. Illustration of the influence of harmonic distortion in the grid on the harmonic distortion of inverter current.

a-b-c: grid voltage, inverter current and harmonic content of inverter current for an undistorted grid voltage.

d-e-f: like a-b-c but for a grid voltage that is distorted with 4\% 3rd (20°) and 3\% 7th harmonic (-10°). As a result, the 3rd harmonic current is decreased and the 7th harmonic current increased.
10. Measurement strategy and setup

In the chapter 7, a model has been proposed to model harmonic distortion from power electronic devices. The aim of this research is to validate the model for solar inverters. This chapter discusses the measurement strategy and the test setup that is used.

10.1 Measurement strategy

In section 7.1, the three most important properties of the model were discussed. They are

- linear relation between harmonic voltage and current
- frequency decoupling (n^{th} harmonic voltage only affects the n^{th} harmonic current)
- harmonics are independent of operating power

The measurement strategy is straightforward: measure the harmonic distortion of the inverter current in an undistorted grid. Then, add a chosen harmonic to the undistorted grid voltage and measure the harmonic current again. Change the amplitude or phase of the harmonic and repeat the current measurement. Do this for a series of amplitudes and phases. The relation between that harmonic voltage and all harmonic currents is then known and linearity can be proven. Additionally, one can determine whether that harmonic voltage also affects other harmonic currents. If this is not the case frequency decoupling is proven. Repeat these measurements for other harmonics. To exclude the influence of the power delivered by the inverter, the DC input conditions are to be kept constant. To find the influence of actual power level, repeat the measurements for other input conditions. A flow chart of the measurement strategy is shown in figure 10-1.

The value of the current source I_{0}(n) for harmonic n in the proposed model is the n^{th} harmonic current measured in an undistorted grid. Y is the gradient of the linear relation between the nth harmonic current I_n and the nth harmonic voltage V_n (Y_n = \frac{dI_n}{dV_n}). Conductance G_n and C_n can be calculated from Y_n as indicated in section 7.2.

To proof a linear relation between two quantities, multiple measurements are required. The measurements should be distributed equally over the interval of interest and more measurements make the proof of linearity more reliable. As both amplitude and phase are to be changed, the number of measurements per harmonic can become large.

![Figure 10-1. Measurement strategy](image-url)
The authors of [1] already assumed that the model was valid. Therefore, they performed only two measurements per harmonic: a measurement at an undistorted grid voltage to determine \(I_0\), and a measurement where one voltage harmonic with certain amplitude and phase was added. From the latter, \(Y\) is determined. Two measurements are enough to determine the offset and gradient of a linear relation, but the relation cannot be proven; two points can always be connected by a straight line. Additionally, the accuracy of the measurement is low when it is based on two points only. As the goal of this investigation is to prove a linear relation, a lot of measurements are performed. A large number of measurements can also be used to derive the accuracy of the model, an important parameter.

10.2 Measurement setup

To perform the measurements outlined in the previous section the measurement setup should be able to

- provide stable and adjustable DC input conditions
- provide a grid voltage with adjustable harmonic distortion
- measure harmonic voltage and current distortion

Additionally, as the number of measurements is very large, the setup should be automated to perform series of measurements autonomously.

A schematic overview of the measurement setup is shown in figure 10-2. It consists of a photovoltaic simulator, a grid simulator, an oscilloscope with voltage and current sensors, a PC and the solar inverter under test.

![Figure 10-2. Inverter test setup. A photovoltaic simulator provides constant and adjustable DC input conditions. A net simulator is used to generate a grid voltage with adjustable harmonic distortion. An oscilloscope records voltage and current at the inverter terminals to determine the harmonic distortion. All equipment is controlled from the PC by Matlab based software.](image)

10.3 Photovoltaic simulator

To provide constant and adjustable DC input conditions, a hardware photovoltaic simulator has been constructed. Compared to real PV generators it is less expensive, requires less space and most important of all, it is fully controllable. As discussed in section 8.2, solar inverters have an MPP tracker that tries to maximise the inverter input power. When a voltage source with current limitation is used to feed the inverter, the MPP tracker will operate the source at its maximum current and a voltage that depends on the MPP algorithm. Most MPP trackers are not designed to handle any other sources than PV generators and consequently the inverter does not operate in a stable point, leading to unreliable measurements.

To overcome this problem, a photovoltaic simulator has been constructed. It is based on the model for photovoltaic generators as discussed in section 8.1. It consists of a current source and
strings of diodes connected in parallel and it has a characteristic that is very close to a real photovoltaic generator. Depending on its configuration it can operate at DC voltages of up to 600V and can deliver up to 3kW. The source current, which represents the irradiation, can be controlled by a DC voltage generated by the function generator built into the oscilloscope.

When a transformerless inverter (see chapter 8) is connected to simulator, the inverter may detect an isolation fault. Transformerless inverters generate a common mode voltage across the DC input terminals and a capacitive current is induced in the grounding circuit. In real photovoltaic plants, there is also a capacitive current to the ground, but it is smaller. The actual current that is induced depends on the topology of the inverter. When the inverter detects a too high common mode current it assumes a ground error or a person touching the solar panels and it switches off. The settings differ from inverter to inverter and because of this problem, only one out of three transformerless inverters that are available in the lab could be measured. The problem is discussed in more detail in section B.1. There, also the construction and operation of the photovoltaic simulator are discussed. In appendix B.5 the Matlab based control functions are listed.

10.4 Grid simulator

A hardware grid simulator (California Instruments MX45) is used to emulate the AC grid. In essence, it is a 4 quadrant power amplifier that can supply voltages at grid level. 4 quadrant operation allows connecting power sources like solar inverters. The energy fed into the simulator is then dissipated. The harmonic distortion of the output voltage can be controlled by uploading one cycle of the desired waveform to the source memory. It can be played back at a desired frequency (in this case 50Hz) and RMS voltage. The bandwidth of the source is high enough to generate harmonic voltages up to the 50th harmonic. The source is controlled over a serial connection. More information about the grid simulator can be found on the website, www.calinst.com. Appendix B.5 contains information on Matlab routines that govern the communication to the source.

10.5 Measure harmonic distortion

A 2-channel oscilloscope records voltage and current at the inverter grid terminals. The signals are loaded into Matlab and the harmonic content of current and voltage is calculated. Appendix B.2 discusses details on harmonic measurements. Matlab routines to control the oscilloscope are listed in appendix B.5.

10.6 Measurement automation and procedures

Matlab routines govern the measurement process. A series of measurements is defined by the user and from that point onwards, the measurements are performed automatically. Distorted waveforms are uploaded to the grid simulator and selected in successive measurements. Measurement data from the oscilloscope is stored on the hard disk. Post processing routines calculate harmonic distortion, convert the data to smaller file formats, produce plots, and calculate model parameters. The measurement process, file formats and post processing routines are discussed in detail in appendix B.3.

10.7 Conclusion

To prove that the proposed model is valid for solar inverters, a measurement strategy is defined. Under stable operating conditions, the grid voltage is distorted with one harmonic voltage at the time and the harmonic current from the inverter is measured. In successive measurements its amplitude and phase are changed. From these results, linearity, frequency decoupling and influence of operating power can be proven or determined and model parameters can be calculated. A measurement setup has been constructed to perform these measurements. A
photovoltaic simulator provides a stable and adjustable operation point and a grid simulator generates the various grid conditions. An oscilloscope is used to measure harmonic distortion. All equipment is controlled from a PC and Matlab based routines govern the automated measurement process.

Figure 10-3. Measurement setup components. (a) DC source and 1 diode module from the PV simulator, (b) California Instruments MX45 grid simulator, (c) Tiepie Handyscope 3.
11. Measurement results

In this chapter measurement results for several inverters are discussed. Graphical representations of the results are shown in appendix A. In section 11.1, examples of plots are given and it is shown how they can be interpreted. Additionally, several quantities that are used in later on are discussed briefly. Details on how plots are generated and how parameters are calculated are discussed in appendix B. From section 11.2 onwards the measurement results are discussed.

11.1 On plots and quantities

11.1.1 Presentation of harmonics in the complex plane

In chapter 7, the proposed model is presented. It was shown that when the amplitude of the harmonic grid voltage is changed, it follows a straight line in the complex plane. When its phase is changed, it follows a circle. In the measurements presented in the appendix, both phase and amplitude are changed. Depicted in the complex plane this yields concentric circles or a star-like shape. If there is a linear relation between harmonic voltage and current, the current measurements form a star-shape as well.

Figure 11-1 shows an example of 3rd harmonic voltages and currents measured at the terminals of one of the tested inverters. The plus-sign indicates the origin of the complex plane. The harmonic voltage has been adjusted to 121 set points with amplitude [0, 0.5, ..., 5%] and phase [0, 30, ..., 330°]. The voltage measurements form the expected star shape. The current plot in figure b also shows a nice star-shape. This indicates that there is indeed a linear relation between harmonic voltage and current. The points indicated by an asterisk are set points where the phase of the harmonic voltage programmed into the source was equal to zero. In this way, it can be worked out which current and voltage points belong together. For convenience, the phase angles are added in figure 11-1. The centre of the current plot is shifted away from the origin and rotated with respect to the voltage plot. Speaking in terms of the proposed model, the shift away from the origin is equivalent to $I_0$. The rotation is equivalent to the phase shift between the harmonic voltage and the current induced in the admittance. The phase shift is between 90 and 180 degrees which indicates that the real part of $Y$ is negative and the imaginary part positive. Consequently, $G$ is negative and $C$ positive. Current and voltage phasors for a measurement where the harmonic voltage was 4% of the fundamental with phase 270 degrees are drawn in the plots.

Due to the limited bandwidth of the net simulator, higher voltage harmonics show an increasing phase lag which is expressed in a clock-wise rotation of the voltage plot. This can be recognised in the complex plots in appendix A. This phase lag is no problem, because for calculations the measured voltage at the inverter terminals is used and not the programmed voltage.

In some figures in appendix A, the complex plots miss several points. These are from measurements where the inverter shut down due to excessive voltage distortion. As they are unreliable, they are taken out during post processing.

11.1.2 Frequency decoupling

An important property of the proposed model is frequency decoupling (see section 7.1). To quantify the influence of a harmonic voltage on other harmonic currents, the standard deviation of all harmonic currents per set of measurements is calculated. When there is no influence, the standard deviation is zero. Figure 11-2 shows an example of a plot where deviations for all harmonics are plotted. The deviation of the 5th harmonic current is the standard deviation of all current measurements in figure 11-1-b. Deviations for the other harmonics are calculated from the
same measurements. Appendix A contains plots like figure 11-2 for all sets of measurements, i.e. where the grid voltage was distorted with a 3\textsuperscript{rd} or 5\textsuperscript{th} or 7\textsuperscript{th}, etc. harmonic voltage. In the measurements used for the two plots shown here, the grid voltage was distorted by a 3\textsuperscript{rd} harmonic. The plot shows that the 3\textsuperscript{rd} harmonic voltage only slightly influences current harmonics other than the 3\textsuperscript{rd}. The crosstalk ratio is defined as the ratio between the largest and the second-largest deviation. A high ratio indicates better frequency decoupling.

![Figure 11-1. Example of measurement results. Shown are voltage (a) and current (b) for the 3\textsuperscript{rd} harmonic in the complex plane. The measurement consists of 121 set points where the amplitude and phase of the harmonic voltage take values $[0, 0.5, \ldots, 5\%]$ and $[0, 30, \ldots, 330\degree]$. All set points with a phase of zero are marked with an asterisk. In the right figure, phasors $I_\omega$, $I$, and $I$ are drawn for the setting $V_n = 4\%$, 270°.](image1)

![Figure 11-2. Plot of the influence of the 3\textsuperscript{rd} voltage harmonic on harmonic currents. The vertical axis shows the standard deviation of the harmonic currents for all measurements where a 3\textsuperscript{rd} voltage harmonic added to the grid voltage (the 3rd harmonic currents are shown in figure 11-1-b). The plot shows that the 3\textsuperscript{rd} harmonic voltage does not influence other current harmonics significantly. The crosstalk ratio indicated in the title of the plot is defined as the ratio between the largest and second-largest deviation.](image2)

11.1.3 Model parameters

From all measurements for a certain harmonic, model parameters are calculated using linear regression. It is a way to determine the best linear relation between two data sets, in this case harmonic voltage and current. For each inverter, a table lists values for the amplitude and phase of $I_\omega$, and for $Y$, $G$ and $C$. Additional to the data in the table, $G$ and $C$ are plotted against the harmonic frequency in two figures.
11.1.4 Model accuracy
The model accuracy describes how good the model can predict the harmonic current for a given harmonic voltage distortion. The error that is introduced consists out of two parts.

The first is due to the influence of other voltage harmonics on the current harmonic that is studied. This error depends on the amplitude of the harmonic voltage and therefore it is not straightforward to quantify. The crosstalk graphs, discussed previously, provide an indication of the error.

The second part of the error is introduced by assuming a linear relation between harmonic voltage and current. Two parameters, $R^2$ and RMSE are used to quantify it. $R^2$ (the coefficient of multiple determination) is split up in a value for the real part of the data set and one for the imaginary part of the data set. They are an indication of the goodness of the regression. A value closer to 1 indicates that the relation between harmonic voltage and current is closer to linear. In essence, it is an indication of how well the model applies for that harmonic current of the inverter. RMSE is the root mean square of the error between the measured harmonic current and the harmonic current estimated by the model. It gives an indication of how precise the model estimates the harmonic current (in these experiments, the error introduced by crosstalk is zero because all other harmonic voltages are zero). A value of 0.5 means that the estimation is accurate up to about 0.5% of the fundamental. Both values for $R^2$ and RMSE are stated in the table with model parameters. Appendix B.3 contains a more detailed discussion on the accuracy of the model and shows how the parameters are calculated. Additionally, the table states the number of measurements used to determine the parameters (indicated in the tables as 'm'). More measurements give a better regression and more reliable accuracy parameters.

11.1.5 Conclusion
Measurement results are presented in various ways. To see the relation between harmonic voltage and current, both are plotted in the complex plane. The way amplitude and phase of the voltage harmonic are changed throughout the measurements leads to a star-like shape in the complex plane. If the relation between harmonic voltage and current is linear, the harmonic current has a star-like shape as well. The displacement of the centre of the current plot indicates $I_e$, the rotation with respect to the voltage plot the value of $Y$.

The influence of a harmonic voltage on other harmonic currents is illustrated in a plot where the standard deviation of all harmonic current measurements is shown for all harmonics. The crosstalk ratio is the ratio between the largest and the second largest deviation.

Model parameters are calculated using regression. A table shows parameters for several harmonics.

The accuracy of the model depends on the cross-influence between harmonics and the error that is introduced by assuming linearity. An indication of first is provided by the crosstalk plots, the latter is indicated by the correlation coefficients $R^2$-real and $R^2$-imag and the relative RMSE.
II.2 Measurement results

In this section, measurement results for several inverters are discussed. The discussion is divided into separate experiments, an index is shown in table 11-1. Graphical representations of the results per measurement are shown in appendix A. Preceding a set of experiments on a certain inverter, technical data of the inverter and the configuration of the photovoltaic simulator and the oscilloscope for the experiments are given.

Table 11-1. Experiment index

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11.2.1 Experiment 1 - Mastervolt Sunmaster 130S

This inverter has a high frequency transformer topology. It is usually designed to be mounted on the back of a solar panel and has nominal power of 110W. In this experiment the inverter is driven at 70% of its rated power.

Frequency decoupling

Table 11-2 gives a summary of the experiment results presented in the appendix. It shows that the cross-influence between harmonics is rather small for odd harmonics. For even harmonics - at least for the 4th and the 6th - the influence is more significant. Inspection of detailed graphs in the appendix shows that even voltage harmonics also generate a 2nd current harmonic. This matter is not further investigated as even harmonics are very rare in the grid.

<table>
<thead>
<tr>
<th>Table 11-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
</tr>
<tr>
<td>ratio</td>
</tr>
</tbody>
</table>

Model compliance and accuracy

The graphs in the appendix show that the complex current plots form very neat concentric circles. It can thus be concluded that there is a linear relation between harmonic voltage and harmonic current. In the complex current plots it can be seen that the rotation of the current plot with respect to the voltage plot approaches 90 degrees for higher frequencies. The reactive part of the current then becomes dominant over the active part and Y is mainly capacitive. Table 11-3 shows model parameters. Figure 11-3 plots G and C against the frequency. G is negative for frequencies up to approximately 1kHz. Above that, G is positive. C is positive and rather constant around 0.75uF. R-square is very close to one which indicates that the relation between harmonic voltage and current is indeed very close to linear. The RMSE is below 0.2% for all harmonics, which confirms that the model is very accurate.

Conclusion

For the Mastervolt 130S, the relation between harmonic voltage and current is very close to linear. The RMSE is below 0.2% for all harmonics. For low frequencies G is negative, increasing towards positive for higher frequencies. C is more or less constant.

Table 11-3. Model and accuracy parameters for experiment 1: Mastervolt Sunmaster 130S.

| n  | |I0| (%) | |I0| (mA) | Phase to | G  | C  | R² (real) | R² (imag) | RMSE (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 4.5 | 13.11 | -12 | -1.28 | 0.75 | 0.98 | 1.02 | 0.08 | 120 |
| 4 | 0.1 | 0.15 | - | -1.23 | 0.79 | 0.97 | 1.04 | 0.06 | 118 |
| 5 | 1.6 | 4.03 | -59 | -1.16 | 0.76 | 0.10 | 1.00 | 0.12 | 114 |
| 6 | 0.0 | 0.13 | - | -1.09 | 0.74 | 1.02 | 0.98 | 0.19 | 102 |
| 7 | 1.4 | 3.90 | -66 | -1.06 | 0.75 | 1.01 | 0.98 | 0.11 | 112 |
| 9 | 1.2 | 3.38 | -75 | -0.95 | 0.75 | 1.02 | 0.98 | 0.10 | 100 |
| 11 | 1.0 | 2.95 | -85 | -0.82 | 0.74 | 1.02 | 0.97 | 0.11 | 94 |
| 13 | 0.9 | 2.52 | -91 | -0.70 | 0.73 | 1.02 | 0.98 | 0.11 | 87 |
| 15 | 0.7 | 2.12 | -95 | -0.59 | 0.73 | 1.02 | 0.97 | 0.06 | 61 |
| 17 | 0.6 | 1.80 | -94 | -0.45 | 0.73 | 1.02 | 0.98 | 0.05 | 59 |
| 19 | 0.6 | 1.64 | -92 | -0.38 | 0.72 | 1.01 | 0.99 | 0.05 | 57 |
| 21 | 0.6 | 1.61 | -90 | -0.10 | 0.71 | 1.01 | 0.98 | 0.19 | 55 |
| 23 | 0.5 | 1.48 | -96 | 0.07 | 0.72 | 1.00 | 0.10 | 0.05 | 54 |
| 25 | 0.4 | 1.24 | -103 | 0.26 | 0.72 | 0.99 | 1.01 | 0.05 | 54 |
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Figure 11-3. G and C plotted against frequency (in harmonic number) for experiment 1: Sunmaster 130S. G is negative for frequencies below 1kHz and positive above. C is constant for all frequencies.
11.2.2 Experiment 2 - Sunmaster 130S - low power

To work out the influence of the actual power level on the generated current harmonics and the model parameters, the previous experiment on the Mastervolt Sunmaster 130S was repeated for a lower power level. The PV simulator DC current is reduced by 50% (1.25A instead of 2.5) whilst the configuration of the PV simulator is unchanged. The operating power is also reduced by approximately 50%, from 70 to 33 Watts. Decreasing the current is analogue to reducing the irradiation of the sun in a real application.

Frequency decoupling

Table II-4 shows a summary of the data presented in the appendix. The ratio between the highest and the second highest current deviation per harmonic is still significant for odd harmonics.

<table>
<thead>
<tr>
<th>n</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>13</th>
<th>15</th>
<th>17</th>
<th>19</th>
<th>21</th>
<th>23</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4</td>
<td>9</td>
<td>5</td>
<td>11</td>
<td>12</td>
<td>9</td>
<td>8</td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Model compliance and accuracy

As can be concluded from the figures in the appendix, the inverter still behaves linear at lower power. Table II-4 shows model component values derived from these measurements and relevant values for the Sunmaster 130S at higher power (previous experiment) are added in brackets. Figure II-4 plots model parameters G and C for both experiments against n.

As was the case with the measurements done on this inverter at higher power, G is negative for lower frequencies and positive thereafter. Additionally, C is rather constant. Compared to experiment 1, I₀ is smaller, however there is no constant scaling factor between the two. The phase angles are also significantly different for some frequencies. G seems to be shifted upwards with respect to the previous experiment. C, on the other hand, has decreased by approximately 15%.

Conclusion

At lower power, the inverter still behaves in a linear way, although model parameters are different. The amplitude of I₀ is lower, but not persistent throughout all frequencies. Also, the phase angle is different. G shows the same relation to frequency, but is shifted upwards with respect to the high power situation. C is constant, but about 15% lower than at high power.
Table 11-5. Model parameters and accuracy for experiment 2: Mastervolt Sunmaster 130S at 33% of nominal power. The values in brackets are from experiment 1 (same inverter at 70% of nominal power) and added for comparison.

| n | | I₀ | | I₀ | | Phase I₀ | | G | | C | | R² | | R² | | RMSE | | m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 8.2 | 8.8 (13.1) | -31 (-12) | -0.43 (-1.28) | 0.66 (0.75) | 1.01 | 0.97 | 0.22 | 40 |
| 4 | 0.0 | 0.0 (0.15) | - - | -0.41 (-1.23) | 0.70 (0.79) | 0.89 | 1.09 | 0.33 | 36 |
| 5 | 4.9 | 5.3 (4.93) | -87 (-59) | -0.35 (-1.16) | 0.65 (0.76) | 1.01 | 0.98 | 0.35 | 39 |
| 6 | 0.1 | 0.1 (0.13) | - - | -0.31 (-1.09) | 0.61 (0.74) | 1.14 | 0.91 | 0.51 | 34 |
| 7 | 2.7 | 2.9 (3.90) | -86 (-66) | -0.27 (-1.06) | 0.64 (0.75) | 1.05 | 0.94 | 0.26 | 36 |
| 8 | 2.1 | 2.9 (3.18) | -81 (-75) | -0.17 (-0.95) | 0.62 (0.75) | 1.04 | 0.94 | 0.39 | 33 |
| 9 | 2.5 | 2.7 (2.95) | -75 (-85) | -0.02 (-0.82) | 0.61 (0.74) | 1.01 | 0.97 | 1.07 | 30 |
| 10 | 1.5 | 1.6 (2.52) | -119 (-91) | 0.03 (-0.70) | 0.59 (0.73) | 1.02 | 0.96 | 1.04 | 29 |
| 11 | 0.7 | 0.7 (2.12) | -161 (-95) | 0.10 (-0.59) | 0.59 (0.73) | 1.02 | 0.97 | 0.38 | 29 |
| 12 | 0.8 | 0.8 (1.80) | -104 (-94) | 0.20 (-0.45) | 0.59 (0.73) | 1.00 | 0.99 | 0.35 | 29 |
| 13 | 1.1 | 1.2 (1.64) | -118 (-92) | 0.24 (-0.28) | 0.59 (0.72) | 0.98 | 1.02 | 0.11 | 28 |
| 14 | 2.6 | 0.6 (1.61) | -108 (-90) | 0.35 (-0.10) | 0.59 (0.71) | 1.01 | 0.98 | 0.12 | 26 |
| 15 | 0.8 | 0.9 (1.48) | -39 (-66) | 0.45 (0.07) | 0.59 (0.72) | 1.00 | 1.00 | 0.06 | 27 |
| 16 | 1.1 | 1.2 (1.24) | -58 (-103) | 0.70 (0.26) | 0.58 (0.72) | 1.04 | 0.95 | 0.56 | 26 |

Figure 11-4. G and C for Sunmaster 130S at 64% (+) and 30% (*) of nominal power plotted against frequency. G is shifted upwards and C has decreased.
11.2.3 Experiment 3 - Mastervolt Sunmaster 1200QS(1)

The Mastervolt Sunmaster 1200QS is an inverter designed for the string concept (see section 8.3) and has a nominal power of 850W and also has a high-frequency transformer topology. As is reported in appendix A.3, the configuration of the photovoltaic inverter for this experiment has an MPP power of more than 850W. The inverter limits its input power by decreasing the input voltage, away from the MPP voltage. It was not intended to operate the inverter in this mode, but it was only found out after the experiments were performed. During operation, the inverter indicated to operate at 75% of its maximum power. Later, it turned out that the nominal power is only 75% of the maximum power. Fortunately, it has no influence on the experiment. The harmonics are generated by the inverting stage that is fed from a DC bus at constant voltage. Hence, the input voltage does not influence the harmonic distortion of the inverter.

Current waveform in an undistorted grid
The first two figures in appendix A.3 show that the inverter has very little current distortion. All harmonics are below 1%. Unlike the Sunmaster 130S, there are some inter harmonics around the fundamental frequency caused by current amplitude variations. These variations probably occur when the MPP tracker breaks the input current to measure the open circuit voltage.

Frequency decoupling
Table II-6 shows a summary of the data presented in the appendix. Because the harmonic distortion is very low, the ratios shown are relatively small as well. This is especially true for the third harmonic that is generally quite large. As with the Sunmaster 130S, even harmonics introduce considerable $2^n$ harmonics.

<table>
<thead>
<tr>
<th>n</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
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<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Model compliance and accuracy
Judging from the figures in the appendix, this inverter is less linear than the previous. It is important to note that the spread of measurements within one data point is low (remember that the most probable value is taken from 5 measurements). This indicates that the displacement of the data points from the ideal star-shape is not due to measurement uncertainty, but really represents the behaviour of the inverter. For higher frequencies, the behaviour gets more linear. This observation is not supported by values for R-square and the RMSE shown in table II-7. They indicate more or less the same accuracy for all harmonics. This contradiction is due to the fact that the harmonic current through the capacitor increases linearly with the frequency. Therefore, the same error appears to be smaller. Note that the RMSE is of the same order of magnitude as $I_o$. The relative accuracy of $I_o$ is therefore low.

$G$ is small compared to $C$. This becomes apparent when studying the figures in the appendix: the current is shifted over close to 90 degrees. As seen before, $G$ increases with frequency, it is however positive for all frequencies. $C$ is again rather constant (omitting the value found for $n=4$, but as discussed before, even harmonics are very rare in distribution networks).

Conclusion
For lower harmonics, this inverter is less linear than the Sunmaster 130S presented in experiments 1 and 2. The calculated model admittance is mostly capacitive. $G$, however small, is positive and increasing with frequency. $C$ is constant around 50uF.
Table 11-7. Model parameters and accuracy for experiment 3: Mastervolt Sunmaster 1200QS.

<table>
<thead>
<tr>
<th>n</th>
<th>Io (%)</th>
<th>Io (mA)</th>
<th>Phase Io (°)</th>
<th>G (mS)</th>
<th>C (μF)</th>
<th>R² (real)</th>
<th>R² (imag)</th>
<th>RMSE (%)</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.9</td>
<td>35.2</td>
<td>-62</td>
<td>0.43</td>
<td>4.54</td>
<td>0.93</td>
<td>0.92</td>
<td>0.23</td>
<td>118</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>1.4</td>
<td>169</td>
<td>1.53</td>
<td>6.97</td>
<td>0.59</td>
<td>1.85</td>
<td>0.49</td>
<td>118</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>21.3</td>
<td>-86</td>
<td>0.52</td>
<td>4.89</td>
<td>1.00</td>
<td>0.97</td>
<td>0.18</td>
<td>120</td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
<td>15.2</td>
<td>-99</td>
<td>0.59</td>
<td>4.83</td>
<td>0.93</td>
<td>1.04</td>
<td>0.26</td>
<td>120</td>
</tr>
<tr>
<td>9</td>
<td>0.3</td>
<td>10.5</td>
<td>-102</td>
<td>0.98</td>
<td>4.89</td>
<td>0.94</td>
<td>1.04</td>
<td>0.28</td>
<td>120</td>
</tr>
<tr>
<td>11</td>
<td>0.3</td>
<td>12.7</td>
<td>-143</td>
<td>1.05</td>
<td>4.89</td>
<td>0.93</td>
<td>1.06</td>
<td>0.37</td>
<td>120</td>
</tr>
<tr>
<td>13</td>
<td>0.1</td>
<td>3.3</td>
<td>-132</td>
<td>1.59</td>
<td>4.91</td>
<td>0.90</td>
<td>1.10</td>
<td>0.41</td>
<td>120</td>
</tr>
<tr>
<td>15</td>
<td>0.1</td>
<td>4.6</td>
<td>-109</td>
<td>1.80</td>
<td>4.86</td>
<td>0.90</td>
<td>1.08</td>
<td>0.32</td>
<td>40</td>
</tr>
<tr>
<td>17</td>
<td>0.3</td>
<td>9.9</td>
<td>-178</td>
<td>1.68</td>
<td>5.01</td>
<td>0.89</td>
<td>1.12</td>
<td>0.30</td>
<td>40</td>
</tr>
<tr>
<td>19</td>
<td>0.1</td>
<td>4.8</td>
<td>72</td>
<td>2.23</td>
<td>4.97</td>
<td>0.88</td>
<td>1.12</td>
<td>0.36</td>
<td>40</td>
</tr>
<tr>
<td>21</td>
<td>0.1</td>
<td>3.7</td>
<td>117</td>
<td>2.06</td>
<td>5.16</td>
<td>0.95</td>
<td>1.05</td>
<td>0.19</td>
<td>40</td>
</tr>
<tr>
<td>23</td>
<td>0.3</td>
<td>10.9</td>
<td>132</td>
<td>2.27</td>
<td>5.14</td>
<td>0.94</td>
<td>1.05</td>
<td>0.41</td>
<td>40</td>
</tr>
<tr>
<td>25</td>
<td>0.2</td>
<td>7.3</td>
<td>94</td>
<td>2.74</td>
<td>5.32</td>
<td>0.95</td>
<td>1.04</td>
<td>0.30</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure 11-5. G and C plotted against frequency. G is small, but positive for all frequencies and increasing. C is constant around 5μF. The value of n=4 (the only even harmonic in this series) is clearly different.
11.2.4 Experiment 4 - Mastervolt Sunmaster 1200QS(2)

There are two Sunmaster 1200QS inverters in the lab. Measuring the second under the same conditions as the first shows whether there are any differences between them. Although no differences are expected to be found, the experiment is important for the interpretation of the results of the experiment 6, where the two inverters are connected in parallel.

Model compliance and accuracy
Per harmonic, less set points have been used, and therefore the complex plots in the appendix have less points. The values for R-square and RMSE indicate a similar accuracy as for the other inverter. Table 11-8 shows model parameters for several harmonic frequencies. The values of the other inverter are added between brackets for comparison. In figure 11-6 G and C are plotted against n for both inverters. The amplitudes of \( I_0 \) show a large deviation. The deviation is within the error indicated by RMSE, so it was expected. G and C are very similar. G is calculated with less accuracy, so a higher deviation is expected.

Conclusions
The two Sunmaster 1200QS inverters have the same model parameters. \( I_0 \) and G are small and are therefore determined with low accuracy. This explains differences.

Table 11-8. Model parameters and accuracy for experiment 4: Sunmaster 1200QS-2. The values in brackets are for Sunmaster 1200QS-1 (meas. 1) and added for comparison.

<table>
<thead>
<tr>
<th>n</th>
<th>|I_0| (mA)</th>
<th>|I_0| (mA)</th>
<th>Phase to f_0 (°)</th>
<th>G (mS)</th>
<th>C (µF)</th>
<th>R^2 (real)</th>
<th>R^2 (imag)</th>
<th>RMSE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.9</td>
<td>33.3 (35.2)</td>
<td>-48 (-52)</td>
<td>0.51 (0.43)</td>
<td>4.26 (4.54)</td>
<td>0.92</td>
<td>0.95</td>
<td>0.21</td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>4.2 (1.4)</td>
<td>63 (169)</td>
<td>1.14 (1.53)</td>
<td>6.70 (6.97)</td>
<td>0.59</td>
<td>1.90</td>
<td>0.57</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>23.0 (21.3)</td>
<td>-75 (-86)</td>
<td>0.97 (0.52)</td>
<td>4.81 (4.89)</td>
<td>0.94</td>
<td>1.01</td>
<td>0.16</td>
</tr>
<tr>
<td>7</td>
<td>0.3</td>
<td>10.6 (15.2)</td>
<td>-67 (-99)</td>
<td>0.17 (0.59)</td>
<td>4.48 (4.35)</td>
<td>0.93</td>
<td>1.02</td>
<td>0.34</td>
</tr>
<tr>
<td>9</td>
<td>0.4</td>
<td>16.0 (10.5)</td>
<td>-123 (-102)</td>
<td>0.78 (0.98)</td>
<td>4.72 (4.89)</td>
<td>0.92</td>
<td>1.03</td>
<td>0.34</td>
</tr>
<tr>
<td>11</td>
<td>0.2</td>
<td>7.0 (12.7)</td>
<td>-133 (-143)</td>
<td>0.85 (1.05)</td>
<td>4.77 (4.89)</td>
<td>0.94</td>
<td>1.02</td>
<td>0.20</td>
</tr>
<tr>
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<td>8.6 (3.3)</td>
<td>-173 (-132)</td>
<td>1.38 (1.59)</td>
<td>4.87 (4.91)</td>
<td>0.93</td>
<td>1.05</td>
<td>0.14</td>
</tr>
<tr>
<td>15</td>
<td>0.2</td>
<td>6.7 (4.9)</td>
<td>-156 (-109)</td>
<td>1.36 (1.80)</td>
<td>4.78 (4.86)</td>
<td>0.87</td>
<td>1.11</td>
<td>0.34</td>
</tr>
<tr>
<td>17</td>
<td>0.2</td>
<td>4.9 (9.9)</td>
<td>-35 (-178)</td>
<td>1.67 (1.68)</td>
<td>4.92 (5.01)</td>
<td>0.91</td>
<td>1.08</td>
<td>0.31</td>
</tr>
<tr>
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<td>9.5 (4.8)</td>
<td>149 (72)</td>
<td>2.22 (2.23)</td>
<td>4.94 (4.97)</td>
<td>0.90</td>
<td>1.09</td>
<td>0.36</td>
</tr>
<tr>
<td>21</td>
<td>0.2</td>
<td>5.7 (3.7)</td>
<td>74 (117)</td>
<td>2.42 (2.6)</td>
<td>5.00 (5.16)</td>
<td>0.89</td>
<td>1.10</td>
<td>0.41</td>
</tr>
<tr>
<td>23</td>
<td>0.3</td>
<td>12.6 (10.5)</td>
<td>12 (132)</td>
<td>2.72 (2.27)</td>
<td>4.78 (5.14)</td>
<td>0.90</td>
<td>1.05</td>
<td>0.51</td>
</tr>
<tr>
<td>25</td>
<td>0.2</td>
<td>6.4 (7.3)</td>
<td>93 (94)</td>
<td>3.26 (2.74)</td>
<td>5.63 (5.32)</td>
<td>0.94</td>
<td>1.02</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Figure 11-6. G and C both Sunmaster 1200QS inverters plotted against frequency. (*) = Sunmaster 1200QS-1, (\( \ast \)) = Sunmaster 1200QS-2. G and C are very similar. G is determined with lower accuracy than C and this explains why there is more deviation in G.
11.2.5 Experiment 5 - Mastervolt Sunmaster 1200QS(1) - low power

The operating power of the Sunmaster 1200QS-1 is decreased by approximately 50%, from 850W to 400W.

Table 11-9 lists model parameters. Values for this inverter at high power are added in brackets. In figure 11-7 G and C for are plotted for both situations.

G is very small compared to C and determined with low accuracy. Therefore, the influence of the power on G is not so relevant. C decreases approximately 10% when the operating power is decreased by 50%. A slight decrease in C was also observed when the power was decreased for the Sunmaster 130S (experiments 1 and 2). There seems to be a pattern, but more investigation is necessary to draw any reliable conclusions.

Conclusion
When the operating power of the Mastervolt Sunmaster 1200QS is decreased by 50%, C is decreased by approximately 10%. This behaviour resembles that for the Sunmaster 130S, but more measurements are necessary to draw any conclusions. The relation to G cannot be determined accurately but its influence in the harmonic current is small.

Table 11-9. Model parameters and accuracy for experiment 5: Sunmaster 1200QS-1 at 50% of nominal power. Values for Sunmaster 1200QS-1 at nominal power are added in brackets for comparison.

<table>
<thead>
<tr>
<th>n</th>
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<th></th>
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</thead>
<tbody>
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<td>-42 (-62)</td>
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<td>4.18 (4.54)</td>
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<tr>
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<td>0</td>
<td>9</td>
<td>17.0 (21.3)</td>
<td>-94 (-86)</td>
<td>0.69 (0.52)</td>
<td>4.63 (4.89)</td>
<td>0.96</td>
</tr>
<tr>
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<td>0</td>
<td>8</td>
<td>14.4 (15.2)</td>
<td>-89 (-99)</td>
<td>0.90 (0.59)</td>
<td>4.52 (4.83)</td>
<td>0.99</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>8</td>
<td>14.9 (10.5)</td>
<td>-121 (-102)</td>
<td>1.19 (0.98)</td>
<td>4.60 (4.89)</td>
<td>0.97</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>5</td>
<td>9.4 (12.7)</td>
<td>-86 (-143)</td>
<td>1.79 (1.55)</td>
<td>4.57 (4.89)</td>
<td>0.97</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>5</td>
<td>9.4 (3.3)</td>
<td>-118 (-132)</td>
<td>2.08 (1.59)</td>
<td>4.78 (4.91)</td>
<td>0.99</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>9</td>
<td>15.5 (4.6)</td>
<td>-154 (-109)</td>
<td>2.32 (1.80)</td>
<td>4.66 (4.86)</td>
<td>0.97</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>6</td>
<td>10.9 (9.9)</td>
<td>-140 (-178)</td>
<td>2.93 (1.68)</td>
<td>4.82 (5.01)</td>
<td>0.99</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>7</td>
<td>12.9 (4.8)</td>
<td>-57 (72)</td>
<td>3.66 (2.23)</td>
<td>4.65 (4.97)</td>
<td>0.97</td>
</tr>
<tr>
<td>21</td>
<td>0</td>
<td>4</td>
<td>6.4 (3.2)</td>
<td>-55 (117)</td>
<td>4.22 (2.06)</td>
<td>4.73 (5.16)</td>
<td>0.95</td>
</tr>
<tr>
<td>23</td>
<td>0</td>
<td>1</td>
<td>3.3 (10.9)</td>
<td>158 (132)</td>
<td>5.41 (2.27)</td>
<td>4.96 (5.14)</td>
<td>0.99</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>2</td>
<td>3.6 (7.3)</td>
<td>170 (94)</td>
<td>5.98 (2.74)</td>
<td>4.95 (5.32)</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Figure 11-7. G and C for experiments 3, and 5. (+) = Sunmaster 1200QS-1, (*) = Sunmaster 1200QS-1 low power.
II.2.6 Experiment 6 - Mastervolt Sunmaster 1200QS(1) and (2) in parallel

In this experiment, the two Sunmaster 1200QS inverters are connected in parallel and a line impedance is connected between the inverters and the grid simulator. The impedance is added to test the inverters in a more realistic situation. The impedance is constructed out of a resistance of 0.16 Ohms in series with an inductance of 375uH (0.12 Ohms at 50Hz). This is in the same order of magnitude as the impedance of a typical low voltage grid. The inverters are each connected to a separate photovoltaic simulator. The total generated power is 1.60 kW, roughly 2 times that of one inverter. The voltage is measured at the inverter terminals, so the effective G and C can be determined. The impedance introduces extra phase lag for higher harmonics generated by the grid simulator. This can be recognised in the complex plots in the appendix.

Model compliance and accuracy

Table 11-10 shows model parameters for this setup. In brackets, the values for the Sunmaster 1200QS-1 and Sunmaster 1200QS-2 are added (G and C are added algebraically, values for $I_o$ are added as vectors). Figure 11-8 plots the parameters against frequency.

$I_o$ can be added taking measurement inaccuracies into account. G is very close to the expected value for low frequencies, but deviates towards higher frequencies. This is probably due to the high measurement inaccuracy for G. The real part of Y is already small compared to the imaginary part for low frequencies. For higher frequencies, this ratio increases even more and the accuracy of G decreases. C is very close to its expected value.

Conclusion

When the two Sunmaster 1200QS inverters are connected in parallel, their model parameters can be added.

Table 11-10. Model parameters and accuracy for experiment 6: Sunmaster 1200QS-1 and Sunmaster 1200QS-2 connected in parallel. The expected values (sum of meas. 3 and meas. 4) are added in brackets for comparison.

| n  | $|I_o|/|I_0|$ (%) | $|I_0|$ (mA) | Phase $I_o$ (%) | $G$ (mS) | $C$ (μF) | $R^2$ (real) | $R^2$ (imag) | RMSE (%) | m  |
|----|----------------|-----------|-------------|--------------|--------|--------|-------------|-------------|--------|----|
| 3  | 1.0            | 63.9 (68.0)| -49 (-55)   | 1.01 (0.94)  | 7.88 (8.80)| 0.94   | 0.87        | 0.27        | 80     |
| 5  | 0.7            | 44.3 (44.1)| -81 (-86)   | 1.55 (1.20)  | 9.44 (9.69)| 1.06   | 0.90        | 0.41        | 80     |
| 7  | 0.4            | 27.7 (24.9)| -87 (-86)   | 1.86 (1.36)  | 9.45 (9.31)| 1.01   | 0.95        | 0.34        | 40     |
| 9  | 0.4            | 23.2 (26.1)| -118 (-115)| 2.38 (1.82)  | 9.88 (9.62)| 0.97   | 1.00        | 0.31        | 40     |
| 11 | 0.2            | 13.4 (19.6)| -109 (-139)| 2.66 (2.43)  | 10.10 (9.66)| 0.94   | 1.06        | 0.36        | 40     |
| 13 | 0.4            | 27.9 (11.3)| -161 (-161)| 3.88 (2.05)  | 10.22 (9.78)| 0.94   | 1.06        | 0.32        | 40     |
| 15 | 0.1            | 5.2 (10.4) | -72 (-137)  | 5.34 (4.47)  | 9.70 (9.64)| 0.90   | 1.10        | 0.31        | 40     |
| 17 | 0.2            | 10.0 (6.7) | -66 (-151)  | 5.72 (3.90)  | 9.96 (9.93)| 0.91   | 1.07        | 0.35        | 40     |
| 19 | 0.4            | 25.4 (11.6)| 160 (125)   | 6.81 (4.65)  | 10.37 (9.90)| 0.93   | 1.04        | 0.35        | 40     |
| 21 | 0.1            | 7.9 (8.8)  | 104 (91)    | 7.91 (4.78)  | 10.38 (10.17)| 0.92   | 1.07        | 0.4        | 40     |
| 23 | 0.3            | 20.8 (11.8)| -5 (65)     | 9.08 (5.53)  | 10.44 (9.91)| 0.94   | 1.05        | 0.34        | 40     |
| 25 | 0.3            | 20.0 (13.7)| 99 (94)     | 12.37 (7.57) | 10.82 (10.35)| 1.00   | 0.99        | 0.4        | 40     |
Chapter 11, Measurement results

Figure 11-8. $G$ and $C$ plotted against frequency. (*) = inverter1 + inverter2 (meas. 3 + meas. 4). (**) = inverter1 and inverter 2 in parallel (with grid impedance between the inverters and the grid simulator).
11.2.7 Experiment 7 - G&H Powertrap 1500

This inverter is also designed for the string concept. It has a nominal power of 1150W. In this experiment it is operated at 940W, 82% of its nominal power. Other than the two previous inverters, it has a net transformer.

The first two figures in appendix A.10, which show the current waveform in an undistorted grid for this inverter, indicate that it produces significant amounts of even harmonics in the range up to the 10th harmonic. Even harmonics cause an anti-symmetry between the first half ([0, \pi]) and the second half ([\pi, 2\pi]) of the waveform and this can be recognised in the waveform of this inverter. On the one hand, the inverter injects even harmonics into the grid, on the other hand the complex current plots show that the inverter starts to malfunction when even harmonics are added to the grid voltage. Figure 11-9 shows the waveform when a 1% 4th harmonic is added to the grid voltage. Several other experiments should be performed to find out under what conditions the inverter generates even harmonics and what causes this malfunction. For now, even harmonics are not considered.

![Current waveform of the G&H Powertrap 1500 when the grid voltage is distorted with a 1% 4th harmonic. There is a current outburst around the zero crossing.](image)

Crosstalk
Table 11-11 shows a summary of the data presented in the appendix. The ratio between the highest harmonic current deviation and the second-highest is large for the lower harmonic but decreases from the 11th harmonic onwards. The figures in the appendix show that higher harmonic voltages evoke significant amounts of lower (even and odd) harmonic currents. The crosstalk figures for n=23 and n=25 also show that a higher harmonic around n=50 is being evoked. It is not clear what causes these effects.

<table>
<thead>
<tr>
<th>n</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>13</th>
<th>15</th>
<th>17</th>
<th>19</th>
<th>21</th>
<th>23</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>ratio</td>
<td>9</td>
<td>9</td>
<td>7</td>
<td>10</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Model compliance and accuracy
The complex current plots show that the relation between harmonic voltage and current is close to linear for odd harmonics. This is also proven by the values for R-square and RMSE shown in table 11-12. Other that was the case for the previous inverter (Sunmaster 1200QS), the real part of Y is not small compared to the imaginary part, resulting in a bigger and more accurate value for G. G is negative for all measured frequencies and there is a slight increase for higher frequencies. C has a more or less constant value of 4uF.
Conclusion

The G&H Powertrap 1500 inverter injects significant amounts of even harmonics into the grid. However, when the grid itself is distorted with even harmonics, the device malfunctions. Grid harmonics from the $11^{th}$ onwards evoke significant amounts of lower, even and odd, harmonics and therefore, the model is less accurate. The relation between the $n^{th}$ harmonic voltage and the $n^{th}$ harmonic current is close to linear. $G$ is negative for all measured frequencies and increases with frequency. $C$ is more or less constant around 4uF.

Table 11-12. Model parameters and accuracy for experiment 7: G&H Powertrap 1500.

| $n$ | $|I_0|$ ($\%$) | $|I_0|$ (mA) | Phase $I_0$ (°) | $G$ (mS) | $C$ (uF) | $R^2$ (real) | $R^2$ (imag) | RMSE ($\%$) | m |
|-----|------------|-------------|----------------|--------|--------|------------|-------------|-----------|----|
| 3   | 1.7        | 74.0        | -110           | -17.9  | 3.38   | 0.89       | 1.06        | 0.50      | 120 |
| 5   | 1.6        | 70.1        | -86            | -18.0  | 3.47   | 0.97       | 1.01        | 0.26      | 120 |
| 7   | 0.8        | 37.1        | -101           | -17.7  | 3.68   | 0.98       | 1.01        | 0.27      | 120 |
| 9   | 0.4        | 19.9        | -141           | -18.6  | 4.02   | 1.00       | 1.00        | 0.17      | 120 |
| 11  | 0.4        | 18.2        | -174           | -18.0  | 4.17   | 1.01       | 0.98        | 0.19      | 119 |
| 13  | 0.4        | 18.4        | 155            | -17.7  | 4.26   | 1.02       | 0.97        | 0.19      | 120 |
| 15  | 0.4        | 17.1        | 136            | -16.3  | 4.11   | 1.02       | 0.97        | 0.16      | 64  |
| 17  | 0.4        | 17.5        | 131            | -16.7  | 4.33   | 1.00       | 0.99        | 0.12      | 64  |
| 19  | 0.4        | 16.0        | 133            | -15.7  | 4.27   | 1.00       | 1.00        | 0.07      | 64  |
| 21  | 0.3        | 15.3        | 133            | -14.6  | 4.14   | 1.01       | 0.99        | 0.12      | 64  |
| 23  | 0.3        | 14.3        | 132            | -13.8  | 4.15   | 0.99       | 1.00        | 0.14      | 64  |
| 25  | 0.3        | 13.5        | 133            | -13.3  | 4.13   | 0.98       | 1.01        | 0.12      | 64  |

Figure 11-10. $G$ and $C$ for G&H Powertrap 1500 plotted against frequency (in harmonic number).
11.2.8 Experiment 8 - Siemens Sitop Solar 1500

The Siemens Sitop Solar 1500 inverter is also designed for the string concept. It has a nominal power of 1500 Watts. In this experiment it is operated at 1.36kW or 91% of its nominal power. The inverter has a transformerless topology. See appendix B.1 for more information on the consequences for the measurement setup.

Compared to the other inverters, the Sitop 1500 has a high harmonic distortion. The distortion around the zero-crossings of the current is particularly high.

Crosstalk

Table 11-13 summarises the results presented in the appendix. The crosstalk ratio is bad for lower harmonics. Judging from the figures in the appendix, this is mainly due to 3rd harmonic currents being evoked by other harmonic voltages. For higher frequencies, the effect decreases.

Table 11-13.

<table>
<thead>
<tr>
<th>n</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
</tr>
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<td>7</td>
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<td>9</td>
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<tr>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
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<td>17</td>
<td>6</td>
</tr>
<tr>
<td>19</td>
<td>7</td>
</tr>
<tr>
<td>21</td>
<td>8</td>
</tr>
</tbody>
</table>

Model compliance and accuracy

The complex current plots for harmonics 3 and 5 show an strange effect. The harmonic current measurements do not form concentric circles, but rather concentric ovals. It seems like the harmonic voltage affects the phase of the harmonic current, but to a lesser extent the amplitude. The effect decreases for n=5 and for n=7 it has disappeared almost completely. Table 11-14 contains model parameters for this inverter. The non-linearity for the 3rd and the 5th harmonic is also indicated by the R-square values that deviate significantly from 1. The RMSE also indicates a low accuracy for harmonics 5 and 7. As pointed out earlier, Iₐ is large for the 3rd and the 5th harmonic. G is positive for all frequencies. Unlike the other inverters that have been tested, G does not rise with frequency. C is more or less constant around 15uF.

Conclusion

The Siemens Sitop 1500 inverter has a linear relation between harmonic voltage and current for all harmonics except the 3rd and the 5th. Those harmonics have a large amplitude compared to the other harmonics and other inverters. There is bad frequency decoupling for lower harmonics because those harmonic voltages affect the 3rd and the 5th harmonic. G is positive for all frequencies, but does not increase with frequency. C is rather constant.

Table 11-14. Model parameters and accuracy for experiment 8: Siemens Sitop 1500.

| n  | |Io| (m%) | |Io| (mA) | Phase | Io | G (mS) | C (µF) | R² (real) | R² (imag) | RMSE (%) | m |
|----|---|----|-----|---|------|-------|-----|-------|--------|----------|--------|----------|---|
| 3  | 17.3 | 688.7 | 1   | 31.9 | 16.0 | 1.99  | 0.57 | 1.52  |
| 5  | 12.0 | 684.3 | 14  | 29.3 | 17.0 | 1.31  | 0.72 | 1.35  |
| 7  | 2.4  | 135.5 | 50  | 21.8 | 16.2 | 0.97  | 1.02 | 0.32  |
| 9  | 1.0  | 55.2  | 7   | 20.9 | 15.3 | 1.02  | 0.98 | 0.16  |
| 11 | 1.6  | 90.6  | -169| 18.3 | 15.2 | 0.99  | 1.01 | 0.36  |
| 13 | 1.5  | 84.8  | -124| 20.1 | 15.0 | 1.04  | 0.96 | 0.33  |
| 15 | 1.0  | 58.1  | -149| 20.8 | 15.4 | 1.01  | 0.99 | 0.13  |
| 17 | 0.2  | 13.1  | -119| 22.2 | 15.9 | 1.01  | 0.99 | 0.06  |
| 19 | 0.6  | 31.9  | 46  | 24.3 | 16.3 | 0.99  | 1.01 | 0.13  |
| 21 | 0.8  | 47.5  | 71  | 24.6 | 16.7 | 0.97  | 1.03 | 0.17  |
| 23 | 0.4  | 23.1  | 60  | 25.3 | 16.5 | 1.00  | 1.00 | 0.15  |
| 25 | 0.3  | 14.7  | 109 | 25.5 | 16.5 | 1.00  | 1.00 | 0.04  |
Figure 11-11. G and C for the Siemens Sitop 1500 as a function of frequency.
11.3 Conclusions

A summary of conclusions from the experiments presented in this chapter are presented here. Chapter 12, conclusions and recommendations, draws more general conclusions about the whole research.

**Even and odd harmonics**
The experiments focus on odd harmonics, since even harmonics are rare in the distribution grid. Additionally, most inverters behave very different when even harmonics are added to the grid voltage.

**Linearity**
For the inverters that have been tested, the relation between harmonic voltage and current is close to linear. The error that is introduced by assuming linearity is below 0.5% in most cases.

**Frequency decoupling**
The influence of a voltage harmonic on other current harmonics differs significantly from one inverter to the other. For some inverters, the influence is small and independent from the frequency of the harmonic voltage that is applied. For other inverters, the influence is more significant and certain patterns appear. In the latter case, the error that is introduced by the cross-influence is higher than the error introduced by assuming linearity. Even harmonics have generally far more cross-influence than odd harmonics.

**Model parameters**
$I_0$, the harmonic current distortion in an undistorted grid, is very different for different types of inverters. For one inverter, all harmonic currents were below 1% of the fundamental when the inverter was operated at nominal power. For another inverter, the 3rd harmonic was almost 20%. Most inverters generate very little even harmonics. For one inverter, significant amounts of even harmonics were observed.

For all inverters it was observed that $C$ is constant for all frequencies. $C$ is larger for inverters with higher nominal power, but a fixed ratio has not been observed. As the current through the capacitive part of $Y$ increases linearly with frequency, $C$ becomes dominant for higher frequencies.

The conductance $G$ depends on the harmonic frequency. Generally, it increases with frequency, but for one inverter this was not the case. $G$ can be negative, positive or both. The capacitive current is dominant for higher harmonics and consequently $G$ is calculated with less accuracy.

$G$ and $C$ are clearly different for even harmonics.

**Influence of operating power**
$I_0$ remains largely unaffected when the operating power is decreased, but $G$ and $C$ change. Two inverters have been tested at nominal and 50% of nominal power and for both inverters $G$ increases and $C$ decreases. The increase in $G$ is significant, although there is no clear relation. $C$ decreases slightly, about 15%.

**Parallel devices**
In one experiment, two equal devices were connected in parallel. From that it can be concluded that model parameters can be added for parallel connection.

Table 11-15 summarises conclusions for each inverter.
<table>
<thead>
<tr>
<th></th>
<th>Mastervolt Sunmaster 130S</th>
<th>Mastervolt Sunmaster 1200QS</th>
<th>G&amp;H Powertrap 1500</th>
<th>Siemens Sitop 1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology</td>
<td>High frequency transformer</td>
<td>High frequency transformer</td>
<td>Net frequency transformer</td>
<td>Transformerless</td>
</tr>
<tr>
<td>System concept</td>
<td>Module integrated</td>
<td>String</td>
<td>String</td>
<td>String</td>
</tr>
<tr>
<td>Nominal power</td>
<td>110W</td>
<td>850W</td>
<td>1500W</td>
<td>1500W</td>
</tr>
<tr>
<td>Freq. decoupling</td>
<td>Very good, ratio &gt; 10</td>
<td>Poor for n &lt; 9 thereafter</td>
<td>Poor. For higher n, higher influence on low (even and odd) harmonics.</td>
<td>Fair, high influence on 3rd and 5th which are large</td>
</tr>
<tr>
<td>Linearity</td>
<td>RMSE &lt; 0.2%</td>
<td>RMSE &lt; 0.4%</td>
<td>RMSE &lt; 0.5%, lower for higher n</td>
<td>Bad for 3rd and 5th, &lt;0.4% for n &gt; 5</td>
</tr>
<tr>
<td>Even / odd harmonics</td>
<td>Even: bad frequency decoupling</td>
<td>Even: bad frequency decoupling</td>
<td>Malfunction for 2nd and 4th harmonic</td>
<td>No data available</td>
</tr>
<tr>
<td>Io</td>
<td>Low, &lt; 4.5%</td>
<td>Very low, &lt; 1.0%</td>
<td>Low, &lt; 1.7% but considerable even harmonics</td>
<td>High 3rd and 5th, &lt; 2.5% for n &gt; 5</td>
</tr>
<tr>
<td>G</td>
<td>Negative, rising with n. Higher for lower power.</td>
<td>Very small, positive, rising with n. Higher for lower power.</td>
<td>Negative for all n but rising</td>
<td>Positive for all n, no clear relation</td>
</tr>
<tr>
<td>C</td>
<td>Constant, 0.75uF at 70% of nom. power, 0.65uF at 33%</td>
<td>Constant, 5uF at 100% of nom. power, 4.6uF at 50%</td>
<td>Constant, 4uF</td>
<td>Constant, 16uF</td>
</tr>
</tbody>
</table>

Table 11-15. Summary of measurement results per inverter.
12. Conclusions and recommendations

12.1 Conclusions

12.1.1 Introduction
Power electronic devices are the main source of harmonic distortion in the distribution grid. Interaction between harmonic voltages in the grid and harmonic currents generated by the power electronic device can cause amplification of harmonics. Resonances between grid inductances and power electronic devices or between devices can occur. A model to describe this interaction is introduced. It consists out of a current source that models the harmonic current distortion in an undistorted grid and an admittance that models the influence of voltage harmonics in the grid. Voltages and currents at each harmonic frequency are modelled by a separate model and hence the values of the current source and the admittance can depend on the frequency. The main properties of the model are

- a linear relation between harmonic voltage and current
- the $n^{th}$ harmonic voltage only influences the $n^{th}$ harmonic current (frequency decoupling)
- values for model components are independent of power level or proportional to it
- component values can be added when multiple devices are connected in parallel

The goal of the research is to validate the model for solar inverters. An automated measurement setup has been constructed. It consists out of a photovoltaic simulator, a grid simulator, an oscilloscope and a PC. The photovoltaic simulator provides stable DC input conditions and can operate the inverter at any power level. The grid simulator can generate a desirable grid distortion. The oscilloscope records voltage and current at the inverter grid terminals to determine the harmonic distortion. A PC with Matlab based software governs the automated measurement process. The measurement strategy is to distort the grid with one harmonic voltage at the time and measure the harmonic current from the inverter (up to the 50th harmonic). In a series of 40 to 120 measurements, the amplitude and phase of the harmonic voltage is changed and the response from the inverter is recorded. To increase measurement accuracy, each measurement is repeated 5 times and the most probable value is determined. The spread between measurements quantify the accuracy of the measurement. The whole set of measurements is repeated for odd harmonics up to the 25$^{th}$. In some experiments, even harmonics 4 and 6 are also tested.

Values for model components for different harmonic frequencies are calculated using linear regression. Regression parameters $R^2$ (the coefficient of multiple determination) and the relative RMSE (root mean square of the estimation error) provide an indication of the accuracy of the model. A parameter, called crosstalk, is introduced to quantify the influence from other harmonic voltages on the harmonic current under consideration. The contribution of partial frequency decoupling depends on the amplitude of the voltage harmonics and is therefore hard to quantify. Graphical representation of the measurement results added in the appendix provide a basis for discussion.

12.1.2 Measurement results
4 commercially available solar inverters of different topology and power rating have been tested. One has a net transformer, two have a high-frequency transformer and one is transformerless. Two of them have been tested at two different power levels and in one experiment two inverters were connected in parallel.
Chapter 12, Conclusions and recommendations

The spread within the 5 measurements performed per set point is small for all experiments. This implies that the measurement data that is used for further calculations is reliable. The large number of set points per harmonic ensures that the accuracy analysis is reliable as well. In general, the inverters all have the major characteristics of the model and thus it can be said that the model can indeed be used to make a reasonable prediction about the harmonic current from solar inverters.

It has been observed that the behaviour of the inverters differs between even and odd harmonics. The model is generally not valid for even harmonics and when it is valid, model parameters are significantly different. Consequently, model component values for odd harmonics cannot be estimated by determining their value for even harmonics, as was suggested in [1].

The relation between harmonic voltage and current is close to linear for all odd harmonics of all tested inverters. The error that is introduced by assuming linearity is generally below 0.5% of the fundamental. For higher harmonics, the harmonic current that is induced by the harmonic grid voltage increases and the relative error decreases.

For most inverters, the frequency decoupling is large. The error that is introduced by voltages at other frequencies depends on the amplitude of the harmonic voltage, but in the range of amplitudes that have been used in these experiments it is in the same order of magnitude as the error due to assuming linearity. For some inverters, the influence on some harmonics (usually the lower) is more significant. The error that it introduces is large compared to the linearity error. For all tested inverters, the value of the capacitor in the model is constant within a band of +/- 10% for all frequencies. The capacitor is larger for inverters of higher power rating, but the scaling factor is not constant. When the inverter operating power is decreased by 50%, the value of the capacitor decreases by approximately 15%, so there is no proportional relation. As the capacitance depends on the operating power, resonances in the network depend on the irradiation of the PV generators. Consequently, resonances can build up and disappear quickly.

The model conductance is not constant. Generally it increases with frequency. For two inverters G is positive for all frequencies, for one inverter G is negative for all frequencies and for the last inverter, G is negative for low frequencies and positive for higher frequencies. For some inverters, the influence of the conductance is small compared to the capacitor. As the frequency increases the reactive current through the capacitor becomes dominant over the active current through the conductance. Consequently, G is negligible for all inverters for higher harmonics.

From one experiment where two inverters were connected in parallel, it can be derived that model components can be added for parallel devices.

The results show that the proposed model can contribute to the understanding and modelling of harmonic interaction between solar inverters and the distribution grid. This research has given answers to a lot of questions, but as always, new ones have come up. Additional research is necessary to answer them.

12.2 Recommendations

This section contains some ideas and recommendations for future research. Additionally, some ideas on how to improve the measurement setup are given.

12.2.1 Future experiments

Test more inverters
Due to lack of time, not all inverters that are available in the lab have been tested. If more inverters are tested, maybe some conclusions can be drawn on the influence of topology on model parameters

Test more inverters at several different power levels
Up till now, two inverters have been tested at two power levels. It revealed that model parameters depend on the operating power. To investigate the relation and to find out whether the relation is
similar for all inverters, a series of inverters should be tested at a range of power levels; for example at 20, 30, ..., 90 and 100%.

*Investigate the impact of frequency coupling in more detail*

As was mentioned in the conclusion, harmonic frequencies are not completely decoupled. For some inverters it was observed that several lower harmonic currents were affected significantly by higher harmonic voltages. The error due to this effect can be studied in more detail by distorting the grid voltage with combinations of harmonics. The measurement software can be easily adapted to accommodate this test.

*Construct, simulate and measure small networks of inverters and cables*

In most experiments, the inverters were connected directly to the grid simulator with very low impedance. This was done to eliminate any influence of the grid impedance. In future experiments, small networks with several inverters and cable impedance in between can be constructed. A rather simple simulation tool can be used to predict harmonic voltages and currents. The simulations can then be compared with measurements. One can also try to evoke resonances to see whether the model can predict those.

*Conduct an extensive field test*

In the Netherlands there are several large solar plants. The solar plant along the A9 highway near Amsterdam is particularly interesting to investigate, because a few hundred small inverters are connected in parallel to a distribution transformer. Because there are few other loads and approximate cable lengths are known, the situation is similar to a lab setup, only much larger. The two inverter types that have been used in that plant are available in the lab (they are borrowed from ECN) so a model of the inverter can be determined. For this research, measurements have been done at that site, but the measurement equipment was not suited for these kind of experiments. It would be best to use the same equipment as in the lab. The HandyScope oscilloscope that is now used in the setup is very convenient for a field measurement.

*Measure other power electronic devices such as TV's computers etc.*

The measurements that have been done so far concentrated on solar inverters. However, the model is also intended to be used for other power electronic devices such as lighting equipment, computers etc. The same setup (without the PV simulator) and measurement software can be used.

### 12.2.2 Measurement setup

*Extend the power of the PV simulator*

Currently, the PV simulator can operate all inverters in the lab at full power. When it was split up, it could barely supply the two inverters in experiment 6 (see section A.6). When more inverters are to be connected in parallel, the PV simulator has to be extended. To reduce the time it takes to construct the diode modules, the design could be changed. Instead of using hundreds of diodes, one could design a circuit with one or several high voltage, high power MOSFET's with a little control circuit. As long as the circuit has a characteristic similar to that of a real photovoltaic generator, it has the same bandwidth, and it can dissipate the energy, it should work well. Additionally, the size and cost of the simulator could be reduced significantly.

*Adapt setup to accommodate all transformerless inverters*

As is described in chapter 10, transformerless inverters generate a common mode voltage at the DC input terminals. This voltage induces a current in the output filters of the current source and two out of three transformerless inverters that are available in the lab detected a too high common mode current and did not switch on. The market share of transformerless inverters is increasing and therefore it is important that they can be tested. It should be investigated which components are critical for the common mode current and measures can be taken to reduce it. An
additional problem is that because of the common mode voltages, the steering option on the PV simulator cannot be used. Delta Elektronika offers isolation devices that can solve this problem.

**Improve measurement software**
Currently, all software is run from the command line. A graphical user interface could be programmed to make the measurement setup more accessible to users.

**GPIB instead of RS232**
Currently, it takes about 30 minutes to complete a set of 40 measurements. With up to 120 measurements per harmonic the total measurement time per setup is around a day. More than half of that time is needed to upload waveforms to the grid simulator and change the current waveform settings. This process is slow, because the communication is done over the serial port. The grid simulator is also equipped with a much faster GPIB port, but that port is not standard available on the PC. Installing a GPIB card or USB to GPIB converter would probably decrease the communication time by more than 90%. This allows doing more measurements in the same amount of time.

**Improve calculation of harmonic distortion**
Another time consuming process is the calculation of the harmonic distortion from the signals recorded by the oscilloscope. Almost all calculation time is dedicated to calculating the exact fundamental frequency. If this process is improved calculation of harmonic frequency can be done while the measurements were performed and the results of the measurement can be presented on the screen immediately. The high number of samples probably makes the algorithm slow. If analogue input filters are used at the input of the oscilloscope, the sample frequency can be reduced. Interpolation can then be used to reach the desired phase accuracy for higher harmonics.
13. References

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A lot of people have contributed to this research in one or another way and I would like to thank them very much. Some people I would like to mention in particular:

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Appendix A - Experiments and results
Appendix A – Experiments and results

A.1 Experiment 1, 2 - Mastervolt Sunmaster 130S - configuration

Mastervolt Sunmaster 130S

Technical information

Grid connection
Nominal power (W) 110
Nominal current (A)

PV connection
MPP range (V) 24 - 40
Maximum voltage (V) 50
Nominal current (A) 3.3
Maximum current (A) 3

Topology
High frequency transformer

Particular details
This inverter is one of two that is installed at the solar plant along the A9 highway near Amsterdam

Experiment 1 configuration

PV simulator
Source 1 x Delta SM3000
Current (A) 2.5
Diodes 48
Uoc (V) 39
Umpp (V) 31
Impp (A) 2.3
Pmpp (W) (Pmpp_rel (% of Pnom)) 70 (64%)

Oscilloscope
channel 2 sensitivity (V) 0.4
channel 2 attenuation 2 (5 loops through CT)
Experiment 2 configuration

**PV simulator**

<table>
<thead>
<tr>
<th>Source</th>
<th>1 x Delta SM3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (A)</td>
<td>1.25</td>
</tr>
<tr>
<td>Diodes</td>
<td>48</td>
</tr>
<tr>
<td>Uoc (V)</td>
<td>37</td>
</tr>
<tr>
<td>Umpp (V)</td>
<td>29</td>
</tr>
<tr>
<td>Impp (A)</td>
<td>1.1</td>
</tr>
<tr>
<td>Pmpp (W) (Pmpp_rel (% of Pnom))</td>
<td>33 (30%)</td>
</tr>
</tbody>
</table>

**Oscilloscope**

| channel 2 sensitivity (V) | 0.4 |
| channel 2 attenuation     | 10 loops through CT |
A.2 Experiment 1 - Mastervolt Sunmaster 130S - results

Waveforms and harmonic distortion in an undistorted grid

Harmonic content of current signal - $I_{fund} = 0.282A$

- 5.68%
- 4.97%
- 4.26%
- 3.55%
- 2.84%
- 2.13%
- 1.42%
- 0.71%
- 0.00%
Appendix A – Experiments and results

Cross-harmonic influence

Crosstalk for N = 3: Ratio = 14

Crosstalk for N = 4: Ratio = 3.1

Crosstalk for N = 5: Ratio = 14

Crosstalk for N = 6: Ratio = 3.7

Crosstalk for N = 7: Ratio = 14

Crosstalk for N = 8: Ratio = 14

Crosstalk for N = 9: Ratio = 14

Crosstalk for N = 10: Ratio = 14

Crosstalk for N = 11: Ratio = 14

Crosstalk for N = 12: Ratio = 14

Crosstalk for N = 13: Ratio = 14
Appendix A – Experiments and results

Crosstalk for N = 15, Ratio = 14

Crosstalk for N = 17, Ratio = 14

Crosstalk for N = 19, Ratio = 14

Crosstalk for N = 21, Ratio = 13

Crosstalk for N = 23, Ratio = 11

Crosstalk for N = 25, Ratio = 10
Appendix A – Experiments and results

Complex voltage and current plots

n = 3 to 13: Amplitude = [0, 0.5, ..., 5.0], Phase = [0, 30, ..., 330]
n = 15 to 25: Amplitude = [0, 0.25, ..., 2.0], Phase = [0, 45, ..., 315]
Appendix A – Experiments and results
A.3 Experiment 2 - Mastervolt Sunmaster 130S - low power - results

Waveforms and harmonic distortion in an undistorted grid

![Waveform graphs showing voltage and current with harmonic content chart]

Harmonic content of current signal - $I_{fund} = 0.108A$
Appendix A – Experiments and results

Cross-harmonic influence

Crosstalk for $N=3$: Ratio $= 7.5$

Crosstalk for $N=4$: Ratio $= 4.4$

Crosstalk for $N=5$: Ratio $= 3.8$

Crosstalk for $N=6$: Ratio $= 4.3$

Crosstalk for $N=7$: Ratio $= 11$

Crosstalk for $N=8$: Ratio $= 12$

Crosstalk for $N=9$: Ratio $= 8.7$

Crosstalk for $N=10$: Ratio $= 8.3$
Appendix A – Experiments and results

Crosstalk for N = 15 - Ratio = 11

Crosstalk for N = 17 - Ratio = 10

Crosstalk for N = 19 - Ratio = 8.5

Crosstalk for N = 21 - Ratio = 8.0

Crosstalk for N = 23 - Ratio = 8.4

Crosstalk for N = 25 - Ratio = 8.0

Crosstalk for N = 27 - Ratio = 8.0

Crosstalk for N = 29 - Ratio = 8.0

Crosstalk for N = 31 - Ratio = 8.0

Crosstalk for N = 33 - Ratio = 8.0

Crosstalk for N = 35 - Ratio = 8.0
Complex voltage and current plots

\[ n = 3 \text{ to } 13: \text{Amplitude } = [0, 1, \ldots, 5.0], \text{Phase } = [0, 45, \ldots, 315] \]
\[ n = 15 \text{ to } 25: \text{Amplitude } = [0, 0.5, \ldots, 2.0], \text{Phase } = [0, 45, \ldots, 315] \]
Appendix A – Experiments and results

A.4 Experiment 3, 4, 5, 6 - Mastervolt Sunmaster 1200QS - configuration

Mastervolt Sunmaster 1200QS

Technical information

Grid connection
Nominal power (W) 850
Nominal current (A)

PV connection
MPP range (V) 120 -350
Maximum voltage (V) 450
Nominal current (A) 5
Maximum current (A)

Topology
High frequency transformer

Particular details
This inverter is installed in the recreational area of Bronsbergen

Experiment 3, 4 configurations

PV simulator
Source 1 x Delta SM3000
Current (A) 4
Diodes 1 string of 7 modules
Uoc (V) 334
Umpp (V) 260
Imp (A) 3.7
Pmpp (W) (Pmpp_rel (% of Pnom)) 950 (112%)
Pac (measured) (W) 856 (100%)

Oscilloscope
channel 2 sensitivity (V) 0.8
channel 2 attenuation 5 (2 loops through CT)
Experiment 5 configuration

**PV simulator**
- **Source**: 1 x Delta SM3000
- **Current (A)**: 4
- **Diodes**: 1 string of 7 modules
- **Uoc (V)**: 334
- **Umpp (V)**: 260
- **Impp (A)**: 3.7
- **Pmpp (W) (Pmpp_rel (% of Pnom))**: 950 (112%)
- **Pac (measured) (W)**: 856 (100%)

**Oscilloscope**
- **channel 2 sensitivity (V)**: 0.8
- **channel 2 attenuation**: 5 (2 loops through CT)

Experiment 6 configuration

Sunmaster 1200QS-I and -2 are connected in parallel. An impedance of 0.16 Ohm (R) and 375uH (L) is connected between the inverters and the grid simulator. The voltage is measured at the terminals of the inverters.

**PV simulator**
- Equal to experiments 3 and 4. A separate PV simulator has been used for each inverter
- **Pac_total (measured) (kW)**: 1.60

**Oscilloscope**
- **channel 2 sensitivity (V)**: 2
- **channel 2 attenuation**: 10 (1 loop through CT)
Appendix A - Experiments and results

A.5 Experiment 3 - Mastervolt Sunmaster 1200QS(I) - results

Waveforms and harmonic distortion in an undistorted grid

Voltage

Current

Harmonic content of current signal - $I_{fund} = 3.89A$
Cross-harmonic influence
Appendix A – Experiments and results
Complex voltage and current plots

n = 3 to 13: Amplitude = [0, 0.5, ..., 5.0], Phase = [0, 30, ..., 330]
n = 15 to 25: Amplitude = [0, 0.5, ..., 2.5], Phase = [0, 45, ..., 315]
Appendix A – Experiments and results
Appendix A – Experiments and results
Appendix A – Experiments and results

Harmonic Voltage for N = 25

Harmonic Current for N = 25

Real part
A.6 Experiment 4 - Mastervolt Sunmaster 1200QS(2) - results

Waveforms and harmonic distortion in an undistorted grid

Harmonic content of current signal - Ifund = 3.68A

![Graph showing harmonic content of current signal with bins and corresponding amplitudes.](image-url)
Cross-harmonic influence

Appendix A – Experiments and results
Appendix A – Experiments and results

Crosstalk for N = 17 - Ratio = 5.3

Crosstalk for N = 19 - Ratio = 5.4

Crosstalk for N = 21 - Ratio = 5.6

Crosstalk for N = 23 - Ratio = 5.5

Crosstalk for N = 25 - Ratio = 5.7
Appendix A – Experiments and results

Complex voltage and current plots

\( n = 3 \) to 13: Amplitude = [0, 1.0, ..., 5.0], Phase = [0, 45, ..., 315]

\( n = 15 \) to 25: Amplitude = [0, 0.5, ..., 2.0], Phase = [0, 45, ..., 315]
Appendix A – Experiments and results
A.7 Experiment 5 - Mastervolt Sunmaster 1200QS(I) - low power - results

Waveforms and harmonic distortion in an undistorted grid

Harmonic content of current signal - Ifund = 1.81A
Appendix A – Experiments and results

Cross-harmonic influence

Crosstalk for N = 3 - Ratio = 4.4

Crosstalk for N = 7 - Ratio = 8.8

Crosstalk for N = 11 - Ratio = 9.8

Crosstalk for N = 5 - Ratio = 7.6

Crosstalk for N = 9 - Ratio = 9.1

Crosstalk for N = 13 - Ratio = 9.9

Crosstalk for N = 15 - Ratio = 6.7

Crosstalk for N = 17 - Ratio = 5.8
Appendix A – Experiments and results

Crosstalk for $N = 19$ - Ratio = 5.5

Crosstalk for $N = 21$ - Ratio = 5.5

Crosstalk for $N = 23$ - Ratio = 5.4

Crosstalk for $N = 25$ - Ratio = 4.7
Appendix A – Experiments and results

Complex voltage and current plots

$n = 3$ to $13$: Amplitude = $[0, 0.5, ... , 5.0]$, Phase = $[0, 45, ... , 315]$

$n = 15$ to $25$: Amplitude = $[0, 0.25, ... , 2.5]$, Phase = $[0, 45, ... , 315]$
Appendix A – Experiments and results

Harmonic Voltage for \( N = 12 \)

Harmonic Current for \( N = 12 \)

Harmonic Voltage for \( N = 13 \)

Harmonic Current for \( N = 13 \)

Harmonic Voltage for \( N = 15 \)

Harmonic Current for \( N = 15 \)

Harmonic Voltage for \( N = 17 \)

Harmonic Current for \( N = 17 \)
A.8 Experiment 6 - Mastervolt Sunmaster 1200QS(1) + (2) - results

Waveforms and harmonic distortion in an undistorted grid

Harmonic content of current signal - Ifund = 7.26A
Appendix A – Experiments and results

Cross-harmonic influence

Crosstalk for N = 3 - Ratio = 1.6

Crosstalk for N = 5 - Ratio = 2.8

Crosstalk for N = 7 - Ratio = 4.7

Crosstalk for N = 9 - Ratio = 4.7

Crosstalk for N = 11 - Ratio = 5.5

Crosstalk for N = 13 - Ratio = 5.8

Crosstalk for N = 15 - Ratio = 5.2

Crosstalk for N = 17 - Ratio = 5.2
Appendix A – Experiments and results

Crosstalk for $N = 19$, Ratio = 6.6

Crosstalk for $N = 21$, Ratio = 6

Crosstalk for $N = 23$, Ratio = 6

Crosstalk for $N = 25$, Ratio = 6
Appendix A — Experiments and results

Complex voltage and current plots

\[ n = 3 \text{ to } 13: \text{ Amplitude} = [0, 1.0, \ldots, 5.0], \text{ Phase} = [0, 45, \ldots, 315] \]

\[ n = 15 \text{ to } 25: \text{ Amplitude} = [0, 0.5, \ldots, 2.5], \text{ Phase} = [0, 45, \ldots, 315] \]
Appendix A – Experiments and results

Harmonic Voltage for N = 11

Harmonic Current for N = 11

Harmonic Voltage for N = 13

Harmonic Current for N = 13

Harmonic Voltage for N = 15

Harmonic Current for N = 15

Harmonic Voltage for N = 17

Harmonic Current for N = 17
Appendix A – Experiments and results
A.9 Experiment 7 - G&H Powertrap 1500 - configuration

G&H Powertrap 1500

Technical information

Grid connection
Nominal power (W) 1150
Nominal current (A)

PV connection
MPP range (V) 175 - 375
Maximum voltage (V) 375
Nominal current (A)
Maximum current (A) 10

Topology
50Hz transformer

Particular details

Experiment configuration

PV simulator
Source 2 x Delta SM3000 in series
Current (A) 5
Diodes 2 strings of 7 modules
Uoc (V) 320*
Umpp (V) 250
Imp (A) 4.6
Pmpp (kW) (Pmpp_rel (% of Pnom)) 1.1 (96%)
Pac (measured) (W) 0.94 (82%)
* The source cannot deliver the open source voltage of this configuration. See appendix B.1 for implications.

Oscilloscope
channel 2 sensitivity (V) 2
channel 2 attenuation 10 (I loop through CT)
A.10 Experiment 7 - G&H Powertrap 1500 - results

Waveforms and harmonic distortion in an undistorted grid

Voltage

Current

Harmonic content of current signal - $I_{fund} = 4.27A$
Cross-harmonic influence

Appendix A – Experiments and results
Appendix A – Experiments and results

Crosstalk for N = 15 - Ratio = 3.5

Crosstalk for N = 17 - Ratio = 4.4

Crosstalk for N = 19 - Ratio = 2.2

Crosstalk for N = 21 - Ratio = 2.9

Crosstalk for N = 23 - Ratio = 1.8

Crosstalk for N = 25 - Ratio = 2.3

Standard deviation of harmonic current (A)
Complex voltage and current plots

n = 3 to 13: Amplitude = [0, 0.5, ..., 5.0], Phase = [0, 30, ..., 330]
n = 15 to 25: Amplitude = [0, 0.25, ..., 2.0], Phase = [0, 45, ..., 315]
Appendix A - Experiments and results
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Appendix A – Experiments and results

A.11 Experiment 8 - Siemens Sitop Solar 1500 - configuration

Siemens Sitop Solar 1500

Technical information

Grid connection
Nominal power (W) 1500
Nominal current (A)

PV connection
MPP range (V) 200 - 520
Maximum voltage (V) 550
Nominal current (A)
Maximum current (A) 6.5

Topology
Transformerless

Particular details

Experiment configuration

PV simulator
Source 2 x Delta SM3000 in series
Current (A) 4
Diodes 1 string of 10 modules
Uoc (V) 477
Umpp (V) 370
Imp (A) 3.7
Pmpp (kW) (Pmpp_rel (% of Pnom)) 1.36 (91%)
Pac (measured) (W)

Oscilloscope
channel 2 sensitivity (V) 2
channel 2 attenuation 10 (1 loop through CT)
Appendix A – Experiments and results

A.12 Experiment 8 - Siemens Sitop Solar 1500 - results

Waveforms and harmonic distortion in an undistorted grid

**Voltage**

- Voltage (V)
- Time (s)

**Current**

- Current (A)
- Time (s)

**Harmonic content of current signal - Ifund = 5.66A**

- Amplitude (A)
- Bin number
- Percentages:
  - 21.22%
  - 17.68%
  - 14.14%
  - 10.61%
  - 7.07%
  - 3.54%
  - 0.00%
Appendix A - Experiments and results

Cross-harmonic influence

[Crosstalk for N = 3 - Ratio = 3.6]

[Crosstalk for N = 5 - Ratio = 3.1]

[Crosstalk for N = 7 - Ratio = 2.6]

[Crosstalk for N = 9 - Ratio = 2.5]

[Crosstalk for N = 11 - Ratio = 3.3]

[Crosstalk for N = 13 - Ratio = 3.8]

[Crosstalk for N = 15 - Ratio = 4.4]

[Crosstalk for N = 17 - Ratio = 4.8]
Appendix A – Experiments and results

Crosstalk for N = 19 - Ratio = 5.8

Crosstalk for N = 21 - Ratio = 6.3

Crosstalk for N = 23 - Ratio = 6.8

Crosstalk for N = 25 - Ratio = 7.5
Complex voltage and current plots

\( n = 3 \) to \( 13 \): Amplitude = \([0, 0.5, \ldots, 5.0]\), Phase = \([0, 45, \ldots, 315]\)

\( n = 15 \) to \( 25 \): Amplitude = \([0, 0.25, \ldots, 2.5]\), Phase = \([0, 45, \ldots, 315]\)
Appendix A – Experiments and results

Harmonic Voltage for N = 11

Harmonic Current for N = 11

Harmonic Voltage for N = 13

Harmonic Current for N = 13

Harmonic Voltage for N = 15

Harmonic Current for N = 15

Harmonic Voltage for N = 17

Harmonic Current for N = 17
Appendix A - Experiments and results
Appendix B - Measurement setup and automation
Appendix B - Measurement setup and automation

B.1 Photovoltaic Simulator

To ensure the inverter under test is operated very close to a field situation, a hardware photovoltaic simulator has been constructed that behaves in a similar way to a real photovoltaic plant.

The model for a photovoltaic array as displayed in figure B1-1 was discussed in chapter 8.

![Photovoltaic Array Model](a)

![Characteristics for Shell Solar PowerMax 150-C module](b)

Figure B1-1
a) Model for an array of photovoltaic cells.
b) Characteristics for a Shell Solar PowerMax 150-C module (estimated from data provided on the internet)

The photovoltaic simulator is constructed according to this model: a current source with strings of diodes connected to it.

B.1.1 Requirements

The photovoltaic simulator is dimensioned to feed a range of small to medium power solar inverters, at least those available in the Power Quality lab at the time. The inverters have input voltage ranges from 50 to 600 Volts and power ratings of 100W to 2.5kW. In the event of an unexpected inverter shut down, the simulator should be able to dissipate the power delivered by the source for an infinite period of time.

B.1.2 Current source

Two Delta SM3000 switch mode power supplies are used as current sources. Each, they deliver a current of up to 10A at a voltage of up to 300V. They can be connected in series to reach the upper voltage requirement and when more current is required, they can be connected in parallel. In case of inverters that operate below 300V, two inverters can be powered at the same time providing there are enough diode modules available (see next section).

The sources have an analogue programming option for both voltage and current. A special device (Master/Slave Series Adapter) can be used to provide equal voltage sharing when the sources are connected in series (see figure B1-2 and source manuals). A special cable provides equal current sharing when connected in parallel. A splitter should then be used to program the master source.

Photovoltaic generators have a very low capacitance where switch mode power supplies have large output capacitance to reduce switching ripple. Therefore, the output capacitance of the sources
has been lowered by a factor of 10 (see High Speed Programming options in the manual). By lowering the output capacitance, the current control is much faster enabling the source to follow the quick voltage changes induced by the MPP tracker in the inverter. The typical capacitance of a photovoltaic generator of 10kW is 1.0μF [4]. The capacitance of the sources is 16μF and they have a bandwidth of approximately 500Hz, depending on the loading of the source (see 'High Speed Programming Options for SM3000). This proved to be fast enough for this application. A side effect is higher switching ripple, but this proved not to be a problem.

**SERIES CONNECTION**

![Series Connection Diagram]

**PARALLEL CONNECTION**

![Parallel Connection Diagram]

Figure B1-2. Setup for series or parallel connection of the two power sources. The master/slave adapters provide equal power sharing. The master source is set to current steering, but voltage steering or combined is also possible.

**B.1.3 Diode strings**

Equal to the design of ECN [9], BYW29 power diodes have been used. They have a voltage-current characteristic which is similar to that of a typical photovoltaic cell (see figure B1-3). Although the open circuit voltage is 40% higher, its curvature is similar. A higher forward voltage is an advantage because it requires less diodes in series to obtain a certain open circuit voltage.

The diodes are arranged in 22 modules that contain 56 diodes each. As such, each module represents a typical 100W solar panel. Multiple strings of modules can be constructed to match the inverter voltage and power rating. Table B1-1 shows some characteristics that can be used to dimension the photovoltaic simulator. Note that these values are valid at room temperature. If the temperature is higher, the voltage across the diodes decreases (see figure B1-7). As a rule of thumb, the voltage in the MPP is 80% of the open circuit voltage and the current in the MPP is 90% of the short circuit current. One module has been split in two parts of 28 diodes. One of those has a special front panel where the string size can be specified exactly. This is used for smaller inverters that operate beneath 50V. Table B1-2 shows four maximum configurations.
Figure B1-3. Characteristic of a typical photovoltaic cell and that of a BYW29 diode connected to a 3A current source.

### Table B1-1. PV simulator characteristics of a configuration with one diode module with 56 diodes and a current source. For multiple modules in series values can be added.

<table>
<thead>
<tr>
<th>Isc (A)</th>
<th>Voc (V)</th>
<th>Vmpp (V)</th>
<th>Impp (A)</th>
<th>Pmpp (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>33</td>
<td>0.9</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>35</td>
<td>1.8</td>
<td>64</td>
</tr>
<tr>
<td>3</td>
<td>46</td>
<td>36</td>
<td>2.7</td>
<td>99</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>37</td>
<td>3.7</td>
<td>136</td>
</tr>
<tr>
<td>5</td>
<td>49</td>
<td>38</td>
<td>4.6</td>
<td>173</td>
</tr>
<tr>
<td>6</td>
<td>49</td>
<td>38</td>
<td>5.5</td>
<td>211</td>
</tr>
</tbody>
</table>

sc = short circuit, oc = open circuit, mpp = maximum power point

### Table B1-2. Four maximum PV simulator configurations with 2 Delta 3000SM sources and 22 diode modules of 56 diodes.

<table>
<thead>
<tr>
<th>Source</th>
<th>String conf.</th>
<th>Isc (A)</th>
<th>Voc (V)</th>
<th>Vmpp (V)</th>
<th>Impp (A)</th>
<th>Pmpp (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 in series</td>
<td>1 x 13</td>
<td>5</td>
<td>600*</td>
<td>491</td>
<td>2.23</td>
<td></td>
</tr>
<tr>
<td>2 in series</td>
<td>2 x 11</td>
<td>10</td>
<td>535</td>
<td>415</td>
<td>3.82</td>
<td></td>
</tr>
<tr>
<td>2 in parallel</td>
<td>3 x 7</td>
<td>15</td>
<td>341</td>
<td>264</td>
<td>3.64</td>
<td></td>
</tr>
<tr>
<td>2 in parallel</td>
<td>4 x 5</td>
<td>20</td>
<td>243</td>
<td>189</td>
<td>3.47</td>
<td></td>
</tr>
</tbody>
</table>

* limited by source voltage

Figure B1-4 shows a graphical representation of the PV simulator working area. Shown are: a 2.5kW constant power line, outer bounds of the diode modules working area and the capabilities of the power source. The MPP power is higher than 2.5kW for 2, 3 and 4 string configuration. In case more power is needed in the 1 string configuration, the current can be pushed over 5A, the modules can handle this current for at least 15 minutes. A higher maximum MPP voltage can be obtained by adding extra modules and starting up the inverter at a lower current (so the open circuit voltage is below 600V) and increasing the current during operation. However, this strategy has some implications for inverters that measure open circuit voltage to determine the MPP voltage (like the Sunmaster 1200QS). Section B.1.8 discusses this subject in more detail.
Appendix B - Measurement setup and automation

Figure B1-4. Working area of the hardware PV simulator when the current through each module is limited to 5A. Shown are a 2.5kW power line (solid), capabilities of the source (-.-), open circuit voltage (--) and MPP voltage (..).

B.1.4 Module construction

Figure B1-5 shows several photographs of a module. The modules are designed to fit 56 diodes and have enough heat sinking capacity to allow a constant diode current of 5A. The dissipated power is then 245W so a large heat sink is necessary. The tab of the diode is connected to its cathode and because the diodes are connected in series, they need to be electrically isolated from the heat sink. This is done through self-adhesive heat conducting isolation tape to speed up the construction process. To ensure good thermal connection, the diodes are pressed in between the heat sinks and the metal plate in between. At the end of this appendix construction drawings are added.

Figure B1-5. A module of the photovoltaic simulator. It contains 56 diodes connected in series. The diodes stick to the heat sinks by means of self-adhesive heat conducting isolation tape. They are pressed in between the metal plate and the sink to ensure good thermal connection.

B.1.5 Heat management

Figure B1-6 shows a thermal model for one module. The heat generated by the diodes is represented by current sources, the various thermal resistances are modelled by resistors and
voltage is equivalent for temperature. Note that the metal plate in between has not been incorporated in the model as its effect is not significant.

Figure B1-6. Thermal model of a diode module. The resistances represent the thermal resistance in the diode itself, over the isolation tape and from the heat sinks to free air. The metal plate in between was not incorporated.

\[ Q_{\text{diode}} = \text{Power dissipated by a single diode} \]
\[ R_{\text{junct-case}} = \text{Thermal resistance between diode junction and diode case} \]
\[ R_{\text{sheet}} = \text{Thermal resistance of isolating sheet} \]
\[ R_{\text{heatsink}} = \text{Thermal resistance of the heat sink (free convection)} \]
\[ T_{\text{ambient}} = \text{Ambient temperature} \]
\[ T_{\text{junct}} = \text{Diode junction temperature} \]

Assuming equal power dissipation in each diode and solving the network for \( T_{\text{junct}} \) yields

\[ T_{\text{junct}} = T_{\text{ambient}} + \frac{Q_{\text{total}}}{N} \cdot \left( R_{\text{sheet}} + R_{\text{junct-case}} \right) \]

Where
\[ T_{\text{ambient}} = 30 \, ^\circ\text{C} \]
\[ R_{\text{heatsink}} = 0.27 \, ^\circ\text{C} / \text{W} \] (effective value for two sinks of 150 mm length)
\[ R_{\text{sheet}} = 0.49 \, ^\circ\text{C} / \text{W} \]
\[ R_{\text{junct-case}} = 2.7 \, ^\circ\text{C} / \text{W} \]

Table B1-3 shows heat sink and diode junction temperature for different currents. Note that these are steady state temperatures and that it takes a long time to heat the sinks as they have a large heat capacity.

**Table B1-3. Heat characteristics of a diode module. Shown are heat sink and diode junction temperatures for different current through the diodes. Values calculated from the model shown in figure B1-6.**

<table>
<thead>
<tr>
<th>I (A)</th>
<th>Pdiss (W)</th>
<th>T_{\text{heatsink}} (^\circ\text{C})</th>
<th>T_{\text{diode junction}} (^\circ\text{C})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>41</td>
<td>44</td>
</tr>
<tr>
<td>2</td>
<td>89</td>
<td>54</td>
<td>59</td>
</tr>
<tr>
<td>3</td>
<td>139</td>
<td>67</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>190</td>
<td>81</td>
<td>92</td>
</tr>
<tr>
<td>5</td>
<td>245</td>
<td>96</td>
<td>110</td>
</tr>
</tbody>
</table>

Figure B1-7 shows results of an experiment where a current of 5A was fed to a module. Over time the heat sink temperature and the voltage were measured. After almost 20 minutes, the temperature has reached 70 degrees and extrapolating the graph verifies that the steady state temperature will indeed be somewhere around 90 degrees although it probably takes almost an hour to reach that. Figure B1-7-b indicates that the voltage across a module is strongly dependant.
on its temperature. Therefore, the temperature should be kept more or less constant during an experiment to keep a stable operating point of the inverter.

Figure B1-7
a) Temperature of a diode module over time when a 5A current is fed through it. The meter used could not indicate above 70 degrees. It shows that the heat sinks have a large heat capacity and that it takes a long time to reach the steady state temperature.
b) Voltage across a module as a function of heat sink temperature. The voltage decreases rapidly with increasing temperature so it is important to keep the temperature more or less constant during an experiment.

B.1.6 Safety
Although the diodes are isolated from the body of the module, capacitive charges or a possible connection after rough handling can lead to dangerous currents through the body as the operation voltage is high. Therefore, it is advisable to connect all modules to earth. During testing, however, it turned out that some modules cannot withstand the high voltages and some sparking occurred. This is probably due to field amplification on the sharp connection leads of the diodes. Extra isolation would probably solve the problem, but due to lack of time it was decided to disconnect the modules from earth.

- When the source is connected to the modules, it is therefore advisable not to touch the modules -

B.1.7 Connection of transformerless inverters
As mentioned in chapter 8, transformerless inverters generate a common mode voltage across the DC input terminal. The actual shape of the voltage depends on the topology of the inverter. The topic is discussed in more detail in [3]. Figure B1-8 shows a schematic of the measurement setup. The DC sources and the inverter are connected to ground via the wall socket. The grid simulator is also grounded via its socket. The two grounds are connected via the distribution rail elsewhere in the building. The impedance is low and can therefore be neglected. The common mode voltage induces a current through the in- and output filters of the DC source, the inverter and the grounding circuit. When the inverter detects a too high common mode current it switches off. This is usually indicated as an isolation fault. The current that is induced depends on the common mode voltage and this depends on the topology of the inverter. Additionally, the safety settings differ from inverter to inverter. Only one out of three inverters that are available in the lab could be switched on. An additional problem is the remote steering of the DC source. The common mode voltage also adds to the steering reference voltage. This can cause dangerous voltages across the oscilloscope. If remote steering is required, one can use the isolation amplifier available from Delta Elektronika (not available in the lab yet, more information: http://www.delta-elektronika.nl/accessories.htm). Due to lack of time the problem was not further investigated, but a minor adaptation of the setup will probably solve it. The next section discusses two options.
Disconnecting the DC source from ground
Disconnecting the inverter from ground will probably not solve the problem, because the current can also flow via the net simulator. Disconnecting the DC source from ground would help, but then the source is not safe to touch. The DC source would have to be controlled remotely and for that, the isolation amplifier can be used.

Coupled inductors
Two coupled inductors between the DC source and the inverter would reduce the common mode current without disturbing the ground circuit. Depending on the shape of the common mode voltage, the inductance of the inductors would have to be large. As the DC current can reach 10A, it wire diameter needs to be large and this increases the size of the inductor.

A more detailed study on how large the common mode voltage is, what frequency it has and where the currents are induced is necessary to find the best solution. [4] contains a chapter on ground currents induced by transformerless inverters.

![Schematic of the measurement setup when a transformerless inverter is connected.](image)

**Figure B1-8.** Schematic of the measurement setup when a transformerless inverter is connected. The common mode voltage at the inverter DC input terminals induces a capacitive current in the ground circuit. When the current is too high, the inverter switches off.

**B.1.8 Operation near the voltage limit of the DC source**
In some experiments described in appendix A, the open circuit voltage of the PV simulator configuration was higher than the maximum voltage of the source and the MPP voltage within the range of the source. This can be the case when the PV simulator is split up into two separate simulators to feed two inverters. Inverters will operate under this condition, but some unwanted effects can occur. When the inverter is switched off in such a configuration, the source cannot supply the voltage and consequently the current decreases. When the inverter starts up, it decreases the voltage across the source and the source current goes back to its desired value. When the inverter uses a tracking algorithm to determine the MPP, there is no problem. However, when the inverter measures the open circuit voltage to estimate the MPP, the MPP voltage will be too low because the open circuit voltage is limited. Consequently, the inverter is operated below the MPP power. One can recognise this by the voltage limitation indicator (LED above the voltage adjustment) in the DC source that blinks shortly approximately every second. It indicates when the source goes from current limitation to voltage limitation. The Mastervolt Sunmaster 1200QS uses the algorithm that measures the open circuit voltage. Possibly there are other inverters in the lab that use it, but details are not available.

**B.1.9 Construction drawings**
On the next pages, construction drawings of the PV modules are added.
Doorsnede AA

Aantal: 20 stuks
Materiaal: aluminium
Aanlevering: koellichaam op maat gezaagd
Omschrijving: PV simulator
Blad nr: 2 van 3
Auteur: A.J.A.Bosman
Contact: 4445 / 0638741632
Co-auteur: Ad van Iersel (4502)
Groep: Fac E, EPS
Aantal: 20 stuks
Materiaal: aluminium
Aanlevering: koellichaam op maat gezaagd
Omschrijving: PV simulator
Blad nr: 3 van 3
Auteur: A.J.A. Bosman
Contact: 4445 / 0638741632
Co-auteur: Ad van Iersel (4502)
Groep: Fac E, EPS
Aantal: 22 stuks
Materiaal: aluminium plaat 2mm
Aanlevering: plaat op maat geknipt
Omschrijving: PV simulator
Blad nr: 1 van 3
Auteur: A.J.A. Bosman
Contact: 4445 / 0638741632
Co-auteur: Ad van Iersel (4502)
Groep: Fac E, EPS
Placing of diodes – Heat sink 1

Projection of wire hole in middle plate

Self adhesive isolation sheet
W1 (RED): Red bus -> hole in plate -> A
W2 (BLACK): B -> hole in plate -> C
W3 (BLUE): D -> Black bus
Totaal lengte hout:
4 * 1585 + 6 * 170 = 8945 mm
Appendix B - Measurement setup and automation

B.2 Harmonic Measurements

To determine the harmonic content of grid voltage and current, both signals are recorded by an oscilloscope and loaded into Matlab. Fitting is applied to determine the exact fundamental frequency and an FFT is used to determine amplitude and phase angle of the harmonics. The next section presents details of sensors, the oscilloscope and several Matlab scripts.

B.2.1 Accuracy and bandwidth

The amplitude of harmonic voltages and currents are roughly in the range of 0 to 8%. An accuracy of at least 0.25% would therefore be appropriate.

The accuracy with which the phase angle can be measured depends on the amplitude of the harmonic. The aim is therefore to have an accuracy of 5° (1.4%) for harmonics of over 1% and 15° (4.2%) for harmonics under 1%. Stated accuracy is for up to the 50th harmonic or 2.5kHz.

B.2.2 Sensors

Voltage sensor

As the output of the net simulator is floating, a differential voltage probe is used. Its output signal is the attenuated voltage difference between the input terminals, but respectively to the ‘zero’ of the oscilloscope. A Tektronix P5200 with 500X attenuation has been used. The common mode rejection ratio is >70dB or <0.3%. In the datasheets, nothing is stated about the accuracy, but that will be at least the same as the CMRR as their bandwidth extends from DC to 25MHz.

Current sensor

A passive current transducer of type Pearson 110S has been used. It has a sensitivity of 100mV/A and an accuracy of <1% which is very high for a passive current sensor. The maximum current-time product is 0.2 or 10A at 50Hz. Depending on the power rating of the inverter, the lead can be put several times through the CT. Its 3dB bandwidth is 1Hz to 20MHz. The theoretical phase error at 50Hz is 1.2° leading. To compensate for this minor phase shift, the CT has been calibrated.

B.2.3 Oscilloscope

Several properties are important for the oscilloscope: vertical resolution and memory size.

Vertical resolution

Most oscilloscopes have a vertical resolution of 8 bit, or 256 discretisation levels, not nearly enough to reach the desired accuracy of 0.25%. 12 bit has 4096 levels or 41 for the lower 1% of the signal and is therefore the absolute minimum. In practice, this is never reached as the signal amplitude does not match the input range exactly.

Sampling frequency and Memory size

The resolution of the FFT algorithm depends on the recorded signal length as Res = 1/Δt or Res = reclength/fsample. Hence, at given record length, lowering the sampling frequency will improve the FFT resolution. However, the sampling frequency has to be higher than the frequency band of the recorded signal to prevent aliasing.

For this setup, a HandyScope from Tiepie engineering is used. It has two channels with up to 25MHz bandwidth, a vertical resolution of up to 16 bit depending on the sample frequency and a memory size of 128kB (or 131060 bytes). Channel 1 is used for voltage measurement and channel 2 for current. Table B2-1 shows the oscilloscope’s settings.
Appendix B - Measurement setup and automation

Table B2-1. Handyscope 3 settings for harmonic measurements.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch. 1 input sensitivity</td>
<td>depends on voltage probe</td>
</tr>
<tr>
<td>Ch. 1 coupling</td>
<td>DC</td>
</tr>
<tr>
<td>Ch. 2 input sensitivity</td>
<td>depends on inverter</td>
</tr>
<tr>
<td>Ch. 2 coupling</td>
<td>DC</td>
</tr>
<tr>
<td>Trigger source</td>
<td>Channel 1</td>
</tr>
<tr>
<td>Trigger level</td>
<td>0 V</td>
</tr>
<tr>
<td>Trigger type</td>
<td>slope, rising</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>625 kHz</td>
</tr>
<tr>
<td>Record length</td>
<td>125400 samples of which 200 pre-trigger</td>
</tr>
</tbody>
</table>

The sample frequency is much higher than would be needed for the bandwidth we are interested in. However, the net simulator produces a considerable switching ripple of 1.2 and 4 times the switching frequency (62.5, 125 and 250kHz). The chosen frequency is thus high enough to prevent aliasing. An input filter would work as well, but as it is not strictly necessary it was left out. The recorded number of samples is enough to achieve an FFT resolution of 5Hz, enough to get a good idea of any interharmonics. 200 samples are added before the trigger and at the end. They are used in the Matlab script and addressed the next section. Communication to the oscilloscope is discussed in appendix B.5

B.2.4 Calculation of harmonic content

The calculation of harmonic distortion is implemented in a Matlab function 'HM5'. Syntax and format of input and output is added at the end of this section.

The FFT (Fast Fourier Transform) algorithm (a computational less demanding implementation of the Discrete Fourier Transform) assumes that the recorded signal is periodical. The provided signal must therefore be exactly n periods. Already a per mille deviation leads to considerable phase errors, increasing for higher harmonics. Windows, like Hann or Hamming, should resolve this problem by gradually attenuating the signal to zero towards its beginning and end, but I did not find them very beneficial in this case. Therefore, a large part of the code is devoted to cutting the recorded signal to n periods as good as possible.

Calculation process overview

The program first cuts the signal to approximate size and later finds the best fit by looking at separate samples. As a start of the signal the first zero-crossing is taken. For this purpose, the 200 extra samples (or 0.6°) are added. Note that a zero-crossing generally does not coincide with zero phase of the fundamental as the sinus is distorted. Although both the oscilloscope and the net simulator have very stable oscillators, there can be a frequency difference which results in a slightly higher or lower fundamental frequency. Therefore, a fitting algorithm is used to determine the exact frequency. It is then used to do an estimation of the position of the corresponding zero-crossing 10 periods further. A few extra samples are added and then the program goes back sample by sample to see which one matches the first sample best. In this way, the signal is as periodic as possible. Because the sample frequency is high, the maximum phase error is 3·10⁻²°. When the signal is distorted by switching noise, looking at the sample value can be inaccurate. To avoid this, the signal is filtered with a very sharp 8th order Chebychev filter. Within its filter band of 5kHz its attenuation is very close to 1 (<1% error). To restore its phase distortion, the signal is filtered a second time backwards. Higher frequencies are then attenuated even further. This way of filtering is non causal, but this is no problem as it is not done in real time. The filter distorts the first and last 8 samples of the signal, so they are removed.

The signal is now exactly n periods long and an FFT is used to transform the signal to frequency domain. Complex values are converted to amplitude (absolute and relative) and phase (in degrees). As the phase of the fundamental is usually not zero, all phases are corrected. The correction increases with the frequency. Finally, all phases are relative to the fundamental which is set to phase zero. When it comes to current, we are interested in the phase relative to the
Appendix B - Measurement setup and automation

voltage fundamental and not the current fundamental. Therefore, current phases are corrected in the same way.

B.2.5 Calibration
To verify that the measurement system works well, two reference signals have been measured: a square wave and a randomly distorted wave. The waveforms are generated by Matlab and loaded into an arbitrary function generator (that is integrated into the HandyScope). The signals are measured through the differential voltage probe to have a realistic calibration.

Square wave
A 50Hz square wave of 10V amplitude was loaded into the function generator and measured back through the differential probe that was adjusted to 50x attenuation for this purpose. A graphical representation of the results is shown in figure B2-1. It shows the relative amplitude for all bins up to 2.5kHz. It shows that there are no side bands around the harmonics which would indicate a non-periodic signal. Table B2-2 contains a comparison between theoretical and actual results. It shows that both amplitude and phase are very accurate. There is a phase error of 1.3° towards the 50th harmonic. This is due to the finite sampling frequency. At 625kHz, the 50Hz fundamental has 12500 samples per cycle, or 0.03 degrees per sample. The 50th harmonic only has 250 samples per cycle, or 1.5 degrees per sample, hence the lower accuracy. Another way to put it, is that the finite sampling rate always introduces some non-periodicity in the signal and thus influences the phase angle of higher harmonics. However, this error is acceptable.

![FFT of the measured square wave with a resolution of 5Hz.](image)

Random harmonics
This signal has random harmonic distortion with a decay in amplitude towards higher harmonics. Table B2-3 shows the loaded and measured waveform distortion. It becomes apparent that the measurement is very accurate, even for very small harmonics.

B.2.6 Conclusion
A wideband passive current probe, a wide band active differential probe and a 2 channel oscilloscope are used to record waveforms. A Matlab script cuts the signal to exactly n periods and calculates the harmonics distortion with a resolution of 5Hz. Tests show that the system has a very good accuracy, more than accurate enough for the measurements performed in this research.
Table B2-2. Fourier transform obtained from the measurement system when a square wave from an arbitrary waveform generator was measured.

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Theoretical Amplitude (%)</th>
<th>Theoretical Phase (degrees)</th>
<th>Measured Amplitude (%)</th>
<th>Measured Phase (degrees)</th>
<th>Harmonic</th>
<th>Theoretical Amplitude (%)</th>
<th>Theoretical Phase (degrees)</th>
<th>Measured Amplitude (%)</th>
<th>Measured Phase (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>0.00</td>
<td>100</td>
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<td>26</td>
<td>0.00</td>
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<td>-</td>
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<td>3</td>
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<td>0.00</td>
<td>-</td>
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<td>-</td>
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<td>-</td>
<td>0.00</td>
<td>-</td>
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<td>0.02</td>
<td>32</td>
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<td>-</td>
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<td>-</td>
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<td>8</td>
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<td>-</td>
<td>0.00</td>
<td>-</td>
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<td>9</td>
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<td>-</td>
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<td>10</td>
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<td>-</td>
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<td>0.00</td>
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<td>9.09</td>
<td>0.05</td>
<td>36</td>
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<td>-</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
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<td>-</td>
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<td>7.69</td>
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<td>-</td>
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<td>-</td>
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<td>0.00</td>
<td>2.56</td>
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<td>0.00</td>
<td>6.66</td>
<td>0.07</td>
<td>40</td>
<td>0.00</td>
<td>-</td>
<td>0.00</td>
<td>-</td>
</tr>
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<td>16</td>
<td>0.00</td>
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<td>0.00</td>
<td>-</td>
<td>41</td>
<td>2.44</td>
<td>0.00</td>
<td>2.43</td>
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<td>17</td>
<td>5.88</td>
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<td>5.88</td>
<td>0.08</td>
<td>42</td>
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<td>0.00</td>
<td>-</td>
</tr>
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<td>0.00</td>
<td>4.76</td>
<td>0.12</td>
<td>46</td>
<td>0.00</td>
<td>-</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>22</td>
<td>0.00</td>
<td>-</td>
<td>0.00</td>
<td>-</td>
<td>47</td>
<td>2.13</td>
<td>0.00</td>
<td>2.12</td>
<td>1.27</td>
</tr>
<tr>
<td>23</td>
<td>4.35</td>
<td>0.00</td>
<td>4.35</td>
<td>0.11</td>
<td>48</td>
<td>2.04</td>
<td>0.00</td>
<td>2.03</td>
<td>1.32</td>
</tr>
<tr>
<td>24</td>
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<td>-</td>
<td>0.00</td>
<td>-</td>
<td>49</td>
<td>2.04</td>
<td>0.00</td>
<td>2.03</td>
<td>1.32</td>
</tr>
<tr>
<td>25</td>
<td>4.00</td>
<td>0.00</td>
<td>3.99</td>
<td>0.12</td>
<td>50</td>
<td>0.00</td>
<td>-</td>
<td>0.00</td>
<td>-</td>
</tr>
</tbody>
</table>
Table B2-3. Fourier transform obtained from the measurement system when a randomly distorted waveform generated by a function generator was measured.

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Input Amplitude (%)</th>
<th>Input Phase (degrees)</th>
<th>Measured Amplitude (%)</th>
<th>Measured Phase (degrees)</th>
<th>Harmonic</th>
<th>Input Amplitude (%)</th>
<th>Input Phase (degrees)</th>
<th>Measured Amplitude (%)</th>
<th>Measured Phase (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>100</td>
<td>0.0</td>
<td>26</td>
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<td>25.0</td>
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<td>25.1</td>
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<td>2</td>
<td>6.30</td>
<td>-112.0</td>
<td>6.32</td>
<td>-111.8</td>
<td>27</td>
<td>2.23</td>
<td>-47.0</td>
<td>2.23</td>
<td>-47.0</td>
</tr>
<tr>
<td>3</td>
<td>3.63</td>
<td>-110.0</td>
<td>3.63</td>
<td>-109.9</td>
<td>28</td>
<td>1.71</td>
<td>73.0</td>
<td>1.71</td>
<td>73.1</td>
</tr>
<tr>
<td>4</td>
<td>5.52</td>
<td>66.0</td>
<td>5.51</td>
<td>66.0</td>
<td>29</td>
<td>0.72</td>
<td>17.0</td>
<td>0.71</td>
<td>17.1</td>
</tr>
<tr>
<td>5</td>
<td>4.25</td>
<td>-71.0</td>
<td>4.24</td>
<td>-71.0</td>
<td>30</td>
<td>3.01</td>
<td>-20.0</td>
<td>3.00</td>
<td>-19.9</td>
</tr>
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<td>0.40</td>
<td>15.0</td>
<td>0.4</td>
<td>15.5</td>
<td>31</td>
<td>2.99</td>
<td>70.0</td>
<td>2.97</td>
<td>70.1</td>
</tr>
<tr>
<td>7</td>
<td>0.24</td>
<td>-126.0</td>
<td>0.24</td>
<td>-126.2</td>
<td>32</td>
<td>2.96</td>
<td>44.0</td>
<td>2.95</td>
<td>44.1</td>
</tr>
<tr>
<td>8</td>
<td>2.76</td>
<td>71.0</td>
<td>2.76</td>
<td>71.0</td>
<td>33</td>
<td>1.85</td>
<td>106.0</td>
<td>1.84</td>
<td>106.1</td>
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<tr>
<td>9</td>
<td>0.11</td>
<td>-44.0</td>
<td>0.11</td>
<td>-44.0</td>
<td>34</td>
<td>2.03</td>
<td>164.0</td>
<td>2.03</td>
<td>164.1</td>
</tr>
<tr>
<td>10</td>
<td>3.23</td>
<td>130.0</td>
<td>3.23</td>
<td>130.0</td>
<td>35</td>
<td>0.42</td>
<td>8.0</td>
<td>0.42</td>
<td>7.5</td>
</tr>
<tr>
<td>11</td>
<td>5.61</td>
<td>127.0</td>
<td>5.61</td>
<td>127.0</td>
<td>36</td>
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<td>137.0</td>
<td>1.47</td>
<td>137.1</td>
</tr>
<tr>
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<td>0.74</td>
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<td>-0.3</td>
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<td>173.0</td>
<td>2.55</td>
<td>173.2</td>
</tr>
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<td>4.67</td>
<td>144.0</td>
<td>4.66</td>
<td>144.0</td>
<td>39</td>
<td>0.73</td>
<td>-82.0</td>
<td>0.73</td>
<td>-81.7</td>
</tr>
<tr>
<td>15</td>
<td>4.52</td>
<td>116.0</td>
<td>4.51</td>
<td>116.0</td>
<td>40</td>
<td>0.63</td>
<td>-89.0</td>
<td>0.63</td>
<td>-88.7</td>
</tr>
<tr>
<td>16</td>
<td>0.11</td>
<td>52.0</td>
<td>0.11</td>
<td>51.2</td>
<td>41</td>
<td>1.97</td>
<td>135.0</td>
<td>1.97</td>
<td>135.1</td>
</tr>
<tr>
<td>17</td>
<td>0.11</td>
<td>114.0</td>
<td>0.11</td>
<td>112.7</td>
<td>42</td>
<td>0.48</td>
<td>85.0</td>
<td>0.48</td>
<td>85.0</td>
</tr>
<tr>
<td>18</td>
<td>1.30</td>
<td>58.0</td>
<td>1.30</td>
<td>58.0</td>
<td>43</td>
<td>1.52</td>
<td>-131.0</td>
<td>1.51</td>
<td>-130.9</td>
</tr>
<tr>
<td>19</td>
<td>3.89</td>
<td>-57.0</td>
<td>3.89</td>
<td>-56.9</td>
<td>44</td>
<td>1.53</td>
<td>-176.0</td>
<td>1.52</td>
<td>-175.8</td>
</tr>
<tr>
<td>20</td>
<td>0.37</td>
<td>-76.0</td>
<td>0.37</td>
<td>-76.0</td>
<td>45</td>
<td>0.35</td>
<td>142.0</td>
<td>0.34</td>
<td>141.9</td>
</tr>
<tr>
<td>21</td>
<td>2.20</td>
<td>-57.0</td>
<td>2.29</td>
<td>-56.9</td>
<td>46</td>
<td>0.31</td>
<td>-108.0</td>
<td>0.31</td>
<td>-107.3</td>
</tr>
<tr>
<td>22</td>
<td>3.82</td>
<td>12.0</td>
<td>3.81</td>
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<td>47</td>
<td>0.05</td>
<td>-72.0</td>
<td>0.05</td>
<td>-72.7</td>
</tr>
<tr>
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<td>4.19</td>
<td>82.0</td>
<td>4.19</td>
<td>82.1</td>
<td>48</td>
<td>0.07</td>
<td>58.0</td>
<td>0.07</td>
<td>58.1</td>
</tr>
<tr>
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<td>3.91</td>
<td>-69.0</td>
<td>3.91</td>
<td>-69.0</td>
<td>49</td>
<td>0.45</td>
<td>-78.0</td>
<td>0.44</td>
<td>-78.0</td>
</tr>
<tr>
<td>25</td>
<td>0.46</td>
<td>122.0</td>
<td>0.45</td>
<td>121.7</td>
<td>50</td>
<td>0.10</td>
<td>-11.0</td>
<td>0.10</td>
<td>-10.8</td>
</tr>
</tbody>
</table>
B.2.7 Matlab function syntax and data format

The algorithm as discussed before is implemented in a Matlab function HM5. Its syntax and input/output data format is given below.

---

**Calculate harmonic content**

```
[Vharm, Iharm, VharmFULL, IharmFULL, V, I] = HM5(voltage, current, fsample, HMSetup)
```

**Description**
Calculates the harmonic content of signals voltage and current.

**Inputs**
- `voltage`: voltage signal
- `current`: current signal
- `fsample`: sample frequency
- `HMSetup`: setup structure with fields
  - `filter`: low pass filtering on (1) or off (0)
  - `window`: Hanning window on (1) or off (0)
  - `currentprobe`: 'pearson' or 'fluke' (see below for details)

**Outputs**
- `Vharm`: voltage harmonics (1 to 50)
- `Iharm`: current harmonics (1 to 50)
- `VharmFULL`: voltage harmonics and inter harmonics (0 to 2.5kHz)
- `IharmFULL`: current harmonics and inter harmonics (0 to 2.5kHz)
- `V`: filtered and adjusted voltage signal
- `I`: filtered and adjusted current signal

**Data formats**

Vharm and Iharm are `[5x50]` matrices that contain the amplitude and phase of harmonics 1 to 50.

- **row 1**: harmonic number \((n = 1, 2, 3, \ldots, 50)\)
- **row 2**: amplitude of harmonic (in V or A)
- **row 3**: amplitude of harmonic relative to fundamental (in %)
- **row 4**: phase angle of harmonic relative to the beginning of the signal (in degrees)
- **row 5**: phase angle of harmonic relative to voltage fundamental if necessary corrected for the error introduced by the current probe.

VharmFULL and IharmFULL have the same format as Vharm and Iharm but contain results for all FFT bins up to 2.5kHz. This allows the user to check for inter harmonics.
### B.3 Measurement procedures

A general measurement procedure is used for all measurements discussed in this report. There are several file formats used to define a measurement, to store data and to summarise processed data. Matlab functions read, write and convert between file types. In the next section, files and procedures are summarised.

#### B.3.1 Measurement definition

All information that is required for one measurement is defined in a Matlab data structure called 'MeasSetup'. It has the following structure:

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>date</td>
<td>date of the measurement</td>
</tr>
<tr>
<td>harmonics</td>
<td>Net simulator settings</td>
</tr>
<tr>
<td>[2x50] array</td>
<td>that determines the waveform (see section function mx45CreateHarmWaveForm)</td>
</tr>
<tr>
<td>voltage</td>
<td>AC fundamental voltage in V (e.g. 230)</td>
</tr>
<tr>
<td>current</td>
<td>AC current limit in A</td>
</tr>
<tr>
<td>phase</td>
<td>phase the inverter is connected to (1, 2 or 3)</td>
</tr>
<tr>
<td>voltrange</td>
<td>net simulator voltage range (ISO or 300)</td>
</tr>
<tr>
<td>PVSetup</td>
<td>Photovoltaic simulator settings and configuration</td>
</tr>
<tr>
<td>source</td>
<td>name and configuration of the DC source(s)</td>
</tr>
<tr>
<td>standbycurrent</td>
<td>DC current during inverter standby</td>
</tr>
<tr>
<td>startupcurrent</td>
<td>DC current during inverter start-up. Lower than 'current' to avoid heating up of the diode arrays</td>
</tr>
<tr>
<td>current</td>
<td>DC current during measurements.</td>
</tr>
<tr>
<td>curramplf</td>
<td>ratio between current and steering voltage. For the SM3000-10 sources it is 2 [A/V]</td>
</tr>
<tr>
<td>startuptime</td>
<td>time the inverter needs to start-up after grid connection</td>
</tr>
<tr>
<td>diodes</td>
<td>number of diodes</td>
</tr>
<tr>
<td>measurement</td>
<td>Measurement information (not setup of oscilloscope)</td>
</tr>
<tr>
<td>stablisetime</td>
<td>time between changing the waveform and doing a measurement in s</td>
</tr>
<tr>
<td>intervaltime</td>
<td>time between measurements</td>
</tr>
<tr>
<td>numberof-</td>
<td>number of measurements per waveform</td>
</tr>
<tr>
<td>measurements</td>
<td></td>
</tr>
<tr>
<td>hs3Setup</td>
<td>Handyscope 3 settings. See function hs3Measure</td>
</tr>
<tr>
<td>HMSSetup</td>
<td>Settings for calculation of harmonic distortion. See function 'HM5'</td>
</tr>
<tr>
<td>inverter</td>
<td>name of the inverter</td>
</tr>
<tr>
<td>netsimulator</td>
<td>name of the net simulator</td>
</tr>
<tr>
<td>filedest</td>
<td>Destination folder of the output files. Should end with ''</td>
</tr>
<tr>
<td>measdata</td>
<td>Measurement data</td>
</tr>
<tr>
<td>voltage</td>
<td>recorded voltage signal</td>
</tr>
<tr>
<td>current</td>
<td>recorded current signal</td>
</tr>
<tr>
<td>time</td>
<td>time base</td>
</tr>
<tr>
<td>voltharm</td>
<td>[n x 5 x 50] matrix with calculated voltage harmonic distortion. See function HM5 for more information.</td>
</tr>
<tr>
<td>currharm</td>
<td>equal to voltharm, but for current distortion</td>
</tr>
</tbody>
</table>

Fields in italics are voluntary fields. They are for later reference only.

Fields with an asterisk (*) are ignored. They are filled in by other scripts later on.
A MeasSetup structure is the recipe for one measurement. An array of structures can be used to define a set of measurements. Usually all information in the structures of such an array is the same except the waveform loaded into the source (MeasSetup.excitation.harmonics), but one can change other parameters if necessary. Various functions such as BuildMeasSetup have been used to generate measurement setup files.

B.3.2 Measurement execution

Function DoMeasurement actually executes the measurements defined in MeasSetup. Its syntax is given below.

**Perform measurement**

\[
\text{DoMeasurement(MeasSetup, DelMode)}
\]

*Description* Perform measurements defined in an array of MeasSetup structures and saves the result in MeasData files.

*Inputs* MeasSetup Array of MeasSetup structures

DelMode Voluntary. If DelMode = 'off' then waveforms are not deleted from the source memory at the start and end of the measurement. By default this option is switched on.

*Outputs* File output Each measurement is stored in a MeasData file.

Because the memory of the net simulator is limited, DoMeasurement divides the measurements up into sets of 41 waveforms. After uploading the first set, the net simulator and PV simulator are set to their start-up settings and a user-defined time is waited for the inverter to start up. Thereafter, voltage and current are checked and the first measurement of the set is started. The waveform is set on the net simulator and after a user-defined time a number of measurements is taken and stored in a MeasData structure and saved to a file. After that, the next waveform is selected and so on. When all measurements of the current set have been completed the net simulator is switched off and the PV simulator is set to its standby settings. A second set of waveforms is uploaded and the cycle begins again.

**Format of MeasData**

The format of MeasData is equal to that of MeasSetup. The fields voltage, current and time in measdata contain measurement data. They are matrices with 'numberofmeasurements' rows and 'reclength' columns.

B.3.3 Calculation of harmonic distortion

The script used to calculate the harmonic distortion is rather slow and therefore it is executed outside the measurement routine. Function CalcHarmDist searches for MeasData files in a specified folder, loads the voltage and current signals and stores the harmonic content in the fields voltharm and currharm in measdata. They are 3-dimensional data structures with 'numberofmeasurement' matrices of 5 rows and 50 columns. For more information on the structure of voltharm and currharm see function HM5. The syntax of CalcHarmDist is shown below.
### Calculate harmonic distortion (for MeasData files)

**CalcHarmDist(Directory)**

**Description**
Loads MeasData files from the specified directory, loads the recorded waveforms and calculates and saves the harmonic distortion back to the files.

**Inputs**
- **Directory**: Location of the files. Should end with '\'.

**Outputs**
- Manipulates files
### B.3.4 Compress data to easy-to-use format

MeasData files contain raw measurement data and have therefore a large file size. Loading and saving them is time consuming. Function ConvertToHarmDataFile picks all necessary measurement results from the MeasData files and puts it onto one data structure of reduced size. Additionally it converts harmonics from amplitude-phase form to complex form, finds the most probable measurement value from multiple measurements and omits measurement sequences where the device under test switched off due to high grid voltage distortion. Later described analysis functions all use the HarmData file format.

HarmData files contain an array of structures that have the following fields.

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>sourceharm</td>
<td>Harmonic distortion of programmed waveform</td>
<td>[2 x 50] matrix. See function mx45CreateHarmWaveForm</td>
</tr>
<tr>
<td>voltharm</td>
<td>measured voltage distortion in amplitude-phase form</td>
<td>[n x 5 x 50] matrix. row 1: harmonic number row 2: absolute value of amplitude row 3: relative (%) value of amplitude row 4: phase in degrees row 5: phase in degrees corrected. columns: harmonic numbers Also see function HM5</td>
</tr>
<tr>
<td>currharm</td>
<td>measured current distortion in amplitude-phase form</td>
<td>equal to voltharm</td>
</tr>
<tr>
<td>voltharmcomplex</td>
<td>measured voltage distortion in complex form</td>
<td>[2 x n x 50] matrix. n = number of measurements per waveform matrix 1: absolute values matrix 2: relative (to fund) values (%) rows: measurements columns: harmonic numbers</td>
</tr>
<tr>
<td>currharmcomplex</td>
<td>measured voltage distortion in complex form</td>
<td>equal to voltharmcomplex</td>
</tr>
<tr>
<td>voltharmcomplexstd</td>
<td>standard deviation of measurements voltharmcomplex</td>
<td>[2 x 50] matrix row 1: absolute values row 2: relative values (%) columns: harmonic numbers</td>
</tr>
<tr>
<td>currharmcomplexstd</td>
<td>standard deviation of measurements currharmcomplex</td>
<td>equal to voltharmcomplexstd</td>
</tr>
<tr>
<td>voltharmcomplexav</td>
<td>most probable value from voltharmcomplex</td>
<td>[2 x 50] matrix row 1: absolute values row 2: relative values (%) columns: harmonic numbers</td>
</tr>
<tr>
<td>currharmcomplexav</td>
<td>most probable value from currharmcomplex</td>
<td>equal to currharmcomplexav</td>
</tr>
</tbody>
</table>
The syntax of ConvertToHarmDataFile is given below:

### Convert to HarmData file structure

ConvertToHarmDataFile(SourceDir, DestDir, FileName)

**Description**  
Summarises measurement results contained in MeasData files to a much smaller data structure: HarmData

**Inputs**

- **SourceDir**  
  Directory where the MeasData files are stored
- **DestDir**  
  Voluntary. Destination directory where the HarmData file is stored. By default equal to SourceDir.
- **FileName**  
  Voluntary. Filename of the HarmData file. By default the filename is HarmData[inverter].mat

**Outputs**  
File output
B.4 Data analysis

The measurement data stored in the HarmData structure is ready for analysis. The next sections describe functions used to display measurement results or calculate certain quantities.

B.4.1 Display measurements in the complex plane

The function PlotHarmInComplexPlane displays harmonic voltages and currents contained in a HarmData data structure in the complex plane. The user can specify which harmonic number is plotted (can be different from the one that is changed in that measurement set) and for which programmed phases. For example one can plot the 5th harmonic voltage and current for measurements where the 7th harmonic was programmed with a phase angle of 30 and 210 degrees. Figures are displayed with a 1:1 aspect ratio to prevent circles to appear as ovals. If desired, the plots can be saved in Matlab (.fig) and Windows Enhanced Meta File (.emf) format.

This function uses GetHarmData to query the HarmData structure. A high-level function called MakePictures uses PlotHarmInComplexPlane to generate plots for all HarmData files in a specified folder. Figure B3-I shows an example of a plot generated by this function.

The syntax of PlotHarmInComplexPlane is given below:

**Plot harmonic voltage and current in the complex plane**

PlotHarmInComplexPlane(HarmData, nget, nsearch, Phase, Mode, OutputFile)

*Description* Queries a HarmData data structure for measurements that satisfy the users requirements, plots the specified harmonic voltages and currents in the complex plane and saves the plots to a file.

*Inputs*  
- **HarmData**: Data structure generated by ConvertToHarmDataFile  
- **nget**: Harmonic number that is to be plotted  
- **nsearch**: Harmonic number that should satisfy the phase requirements  
- **Phase**: Array of phase requirements  
- **Mode**: 'abs' for absolute values in V or A, 'rel' for relative values in %  
- **OutputFile**: Voluntary. Path and name of the output file. For voltage plots '- voltage' is added to the name, '- current' for current plots. Files are save in .fig (Matlab) and .emf (Windows) file format.

*Outputs*  
- **Optional file output**

![Example plots generated by PlotHarmInComplexPlane](image)
B.4.2 Analyse cross influence between harmonics

CalcCrossTalk determines the influence of harmonic voltages on currents at other harmonic frequencies. For all measurements within a HarmData structure it calculates the standard deviation of all harmonic currents. The greater the influence on a certain harmonic, the higher the standard deviation. When there is no influence at all, the standard deviation is zero. The crosstalk ratio is defined as the ratio between the highest and the second highest deviation. The deviation of the harmonic that is changed throughout the different voltage set points is generally the largest. CalcAllCrossTalks calls CalcCrossTalk for all HarmData files and plots the results in bar-plots. The plots are saved in Matlab (.fig) and Windows (.emf) format. An example of a plot is shown in figure B3-2.

![Figure B3-2. Example of a plot generated by CalcAllCrossTalks.](image)

The syntax of CalcAllCrossTalks is given below:

**Determine and display cross harmonic interference**

\[
[crosstalk, ratio] = \text{CalcAllCrossTalks(SourceDir, DestDir)}
\]

**Description**
Calculates the standard deviation of harmonic currents in measurement sets saved in the source directory. A graphical representation is generated and saved.

**Inputs**
- **SourceDir**: Directory where HarmData files are stored. The path should end with `\`.
- **DestDir**: Directory where the output files are stored. Output files are named 'CrossTalk - N=[n]' and saved in Matlab (.fig) and Windows (.emf) file format.

**Outputs**
- **crosstalk**: An array of m [2 x 50] matrices where m is the number of HarmData files. The first row contains standard deviations for all 50 harmonics of absolute measurements, the second row for relative measurements.
- **ratio**: Array of m crosstalk ratios.
B.4.3 Determine model parameters

CalcImpedanceRegression calculates model parameters for a certain harmonic frequency for the model discussed in chapter 7. It queries all nth harmonic voltages and currents from a HarmData file (n is the harmonic number that was changed throughout that set of measurements). This yields a data set that is used for calculations.

There are two ways of calculating model parameters: averaging and regression.

**Averaging**

\( I_0 \) is the harmonic current measured when the grid is undistorted. Then, for each successive measurement \( Y \) can be calculated as \( Y = (I - I_0) / V \), where \( I \) is the harmonic current measured when the voltage is distorted with harmonic voltage \( V \). When the inverter behaves perfectly linear, \( Y \) is the same for each measurement. In practice this is not the case and it turns out that there can be a large spread. This has two main reasons. The first is that \( I_0 \) is determined from only one measurement. A displacement of that data point has influence on all other calculations. The second is that data points close to \( I_0 \) are very unreliable. Dividing two small numbers introduces large errors. When the spread in \( Y \) is much larger than the average one cannot draw any reliable conclusions and therefore this calculation method is not suitable for most inverters.

**Regression**

Linear regression is a method to find a linear relationship between data sets. It finds coefficients \( a \) and \( b \) in the expression \( I = aV + b \) such that the square error that is introduced is minimal. \( I_0 \) is equal to the offset term \( b \) and \( Y \) is equal to gradient \( a \) (\( a = dI/dV \)). Note that both data sets are complex and that \( I_0 \) and \( Y \) are complex as well. The advantage of this method is that \( I_0 \) and \( Y \) are determined from all data points and describe the linear relation in the best way possible. Figure B3-3 shows an example of a data set and the fitted line. For convenience the line is plotted for each phase separately to prevent the line from going from the tip of the star to the centre with every phase change. Note however that it is not necessary to calculate \( Y \) and \( I_0 \) for each phase separately.

**Accuracy**

It is not really relevant to try and determine the accuracy of \( I_0 \) and \( Y \). In the end, we want to predict the harmonic current, so it is more meaningful to get an idea of the accuracy of that. The model accuracy to predict a certain harmonic current depends on two factors: 1) the influence of other harmonic voltages, 2) the error introduced by assuming linearity. The cross influence between harmonics as discussed in the previous section gives an indication of the first, but the actual influence depends on the amplitude of the harmonic voltage. Therefore, this error is not straightforward to quantify. An estimation for the second is determined by two different parameters: RMSE and \( R^2 \).

RMSE is the Root Mean Square of all errors introduced by the regression, i.e. the measured harmonic currents minus the predicted ones. Both data sets are complex, but as we are interested how many "mA's" the model miss-predicts the harmonic current, the absolute value of the error is taken.

In formula: \( \text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\hat{y}_i - y_i)^2} \), where \( \hat{y}_i \) is a predicted value and \( y_i \) is a measured value. The function CalcImpedanceRegression also returns the RMSE in percentage of the fundamental current. That value is presented in the tables in chapter 11.

Another very common parameter to describe the goodness of a regression is the R-square. R-square is the ratio of the SSR (sum of squares of the regression) and SST (sum of squares around the average).
In formula: \( R^2 = \frac{SSR}{SST} \), where SSR = \( \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2 \) and SST = \( \sum_{i=1}^{n}(y_i - \bar{y})^2 \) for \( \hat{y}_i \) is a predicted value of the dependant data set, \( y_i \) the corresponding real value of the dependant data set and \( \bar{y} \) the average of the dependant data set. There are several interpretations of R-square, but in essence it tells something about how well the fit describes the dynamics in the data set. For real data sets, R-square lies in the interval \([0,1]\) where a value closer to one indicates a better fit. For complex data sets however, it is not straightforward to calculate R-square. Therefore, R-square is calculated for the real and imaginary part of the data set separately. This can however result in values above one. This is due to the fact that the real and imaginary parts of the data are coupled. The fit that is good for the real part can be bad for the imaginary part or vice versa. R-square does not provide a confidence bound for any of the model parameters, but it provides an indication of how good the data points can be fitted to a straight line.

Figure B3-3. Example of a data set (dots) and fitted line (-). R-square for the real part of the data set is 0.93 and 1.06 for the imaginary part. The values are close to 1 and this indicates a good fit which is also shown by the plot. The RMSE of the regression is 0.37% of the fundamental also indicating a high accuracy.

Calculation of \( G \) and \( C \)

\( G \) and \( C \) can be calculated from \( Y \) as \( G = \text{real}(Y) \) and \( C = \text{imag}(Y)/100\pi \). As was the case with \( Y \), it is difficult to derive the accuracy of \( G \) and \( C \). Generally, the real part of \( Y \) is small compared to the imaginary part (\( Y \) is mostly capacitive). \( G \) is therefore small and is calculated with less accuracy than \( C \). This is not really a problem, since it is the accuracy of the predicted harmonic current that matters in the end. The latter is indicated by R-square and the RMSE.

The syntax CalcImpedanceRegression and CalcModelRegression, which copies model parameters into a data structure, are given below. Additionally the syntax of CalcAllModels (calculate all models of an inverter) is added.
Appendix B - Measurement setup and automation

Determine model parameters using regression

\[ I_o, Y, Z, R, G, C, L, R_{sreal}, R_{simag}, \text{RMSE}, \text{RMSErel}, n \] = CalcImpedanceRegression(HarmData, n, Phase, Plotmode)

**Description**
Calculates complex conductance model parameters using regression.

**Inputs**
- **HarmData**: HarmData file structure generated by ConvertToHarmDataFile
- **n**: Harmonic the model is to be calculated for
- **Phase**: Array of phases. The model can be calculated for one or more phase angles of the programmed harmonic. Usually one specifies all available phases.
- **Plotmode**: Voluntary. If 'true' then a plot with data points and the fitted line (like figure B3-3) is generated.

**Outputs**
- **I_o**: Offset harmonic current
- **Y**: Admittance
- **Z**: Impedance
- **G**: Conductance
- **R**: Resistance
- **C**: Capacitance
- **L**: Inductance
- **R_{sreal}**: R-square for real part of data set
- **R_{simag}**: R-square for imaginary part of data set
- **RMSE**: RMSE of the regression in Amperes
- **RMSErel**: RMSE relative to the fundamental current in %
## Calculate all models of an inverter

\[
\text{Models} = \text{CalcAllModels(SourceDir, narray)}
\]

**Description**  
Calculates model parameters for several HarmData data structures.

**Inputs**  
- **SourceDir**  
  Directory where HarmData files are stored. It should end with '\.'.
- **narray**  
  Array of harmonic numbers the model should be calculated for. If for example you have HarmData files for \( n=3 \), and \( n=5 \), \( \text{narray} = [3, 5] \)

**Outputs**  
- **Models**  
  Array of Model structures. Each model has the following fields:
  - **n**  
    Harmonic number
  - **Io**  
    \( I_o \) in complex form
  - **absIo**  
    Absolute value of \( I_o \)
  - **phalIo**  
    Phase of \( I_o \)
  - **Y**  
    Admittance determined from regression
  - **stdY**  
    Standard deviation of all \( Y \)'s determined for each data point (see text)
  - **G**  
    Conductance determined from regression
  - **stdG**  
    Standard deviation of all \( G \)'s determined from each data point (see text)
  - **C**  
    Capacitance determined from regression
  - **stdC**  
    Standard deviation of all \( C \)'s determined from each data point (see text)
  - **Rsreal**  
    \( R^2 \)-square of the regression for the real part of the data set.
  - **Rsimag**  
    \( R^2 \)-square of the regression for the imaginary part of the data set.
  - **nmeas**  
    Number of measurements the parameters were calculated from.
Appendix B - Measurement setup and automation

B.5 Test automation

This appendix deals with the communication between the net simulator, the oscilloscope, the current source and the computer. The communication is governed by Matlab functions. Matlab was chosen because it is standard software on the university. In each section, a list of function with a short description is added. For details, refer to the code itself.

B.5.1 Net simulator

The California Instruments mx45 has an RS232 (standard serial) and GPIB communication port. GPIB is much faster than serial, but as no GPIB card for the computer was available, RS232 has been used.

The mxGUI is a user interface that comes standard with the mx45. It communicates over RS232 or GPIB and it can be used to adjust all preferences in the source. One can upload waveforms, set voltage levels, etc. and there is a set of standard IEC tests that can be run.

For custom communication, there are two ways of communicating with the source. There is an extensive C library downloadable from the Cal. Inst. website. Matlab can call C libraries directly, but the functions require a lot of overhead. The mx45 also accepts SCPI (Standard Commands for Programmable Instrumentation1) commands, a text based communication standard for laboratory instrumentation. SCPI commands are high level and as they are text based they require less overhead. There is no manual with SCPI commands for the mx45, but there is an option in the mx45 that shows the commands that are being sent. In this way, one can find out the commands easily.

The Matlab Instrumentation Toolbox (not installed by default, but available on campus license) contains functions that can set up communication over various ports, under which are RS232 and GPIB. One can write and read text strings from an to the port to send and receive SCPI commands.

The next section contains a list of functions related to mx45 net simulator.

B.5.2 mx45 Matlab communication routines

Initialise the instrument

[Error, DeviceName, InstrHandle] = mx45Init(BaudRate)

Description

Opens a connection over RS232 with the instrument. It tries to connect at all available serial ports. The specified baud rate should match that of the instrument. By default it is 38400 b/s. If no connection could be established, an Error = 1. If there already is an active connection, it is closed and reopened.

Inputs

BaudRate

Baudrate of the connection.

Outputs

Error

o: no errors
1: no serial ports detected
2: no instrument detected

DeviceName

Name of the device

InstrHandle

Matlab serial port handle. Pass this to other functions.

1 For more information see www.scpiconsortium.org
Appendix B - Measurement setup and automation

Close the instrument

Error = mx45Close(InstrHandle)

_description_ Closes the connection to the instrument and opens the output relay if it was closed.

_Init_ InstrHandle Handle to the instrument, obtained from mx45Init

_outputs_ Error o: no errors
1: output was already closed
2: failed to close connection

Send / receive a command

[Answer, Statuscode, SystemError] = mx45SendCommand(InstrHandle, Command)

_description_ Low level function that sends a text command to the instrument and returns the 'answer' if any.
Example: [ans, status, systerr] = mx45SendCommand(myinstr, 'IDN?') will give ans = "California instruments ... etc. ..."

_Init_ InstrHandle Handle to the instrument, obtained from mx45Init
Command Text string with the command.

_outputs_ Answer Text string that was returned by the instrument.
Statuscode This option is disabled. Should give information on the system status
Systemerror This option is disabled. Should give information on system errors

Close the output relay

Error = mx45CloseOutput(InstrHandle)

_description_ Closes the output relay, i.e. switches on the output.

_Init_ InstrHandle Handle to the instrument, obtained from mx45Init

_outputs_ Error o: there was no fault
1: there was an error communicating to the instrument

Open the output relay

Error = mx45OpenOutput(InstrHandle)

_description_ Opens the output relay, i.e. switches off the output.

_Init_ see mx45CloseOutput

_outputs_ see mx45CloseOutput
Appendix B - Measurement setup and automation

Set voltage range

Error = mx45SetVoltRange(InstrHandle, Range)

Description
Set the voltage range of the instrument. There are two ranges: 150V and 300V.

Inputs
- InstrHandle: Handle to the instrument, obtained from mx45Init
- Range: Voltage range. Valid values are 150 and 300

Outputs
- Error
  - 0: no errors
  - 1: Range not valid

Set AC output voltage

Error = mx45SetACVolt(InstrHandle, Channel, Voltage)

Description
Sets the output voltage of one or more channels. The voltage should be within the voltage range. If it exceeds that range, the voltage is set to its maximum. To set the voltage range, use mx45SetVoltRange. The specified voltage is the RMS voltage of the selected waveform.

Example: mx45SetACVolt(myinstr, [1, 2, 3], [230, 0, 0]).

Inputs
- InstrHandle: Handle to the instrument, obtained from mx45Init
- Channel: Array of maximum length 3 that contains channel numbers. Valid channel numbers are 1, 2, 3.
- Voltage: Array of the same length as Channel that contains voltage levels.

Outputs
- Error
  - 0: no errors
  - 1: voltage was not set to the desired value

Set current limit

Error = mx45SetCurrLimit(InstrHandle, Channel, Current)

Description
Sets the current limit for one or more channels. The current should be within the current range that depends on the voltage range. 125A for 150V range and 62.5A for 300V range. If the value is out of range, it is set to its maximum. Use mx45SetVoltRange to set the voltage range.

Inputs
- InstrHandle: Handle to the instrument, obtained from mx45Init
- Channel: Array of channel numbers. See mx45SetACVolt.
- Current: Array of current limits. Comparable to mx45SetACVolt.

Outputs
- Error
  - 0: no errors
  - 1: current was not set to the desired value
Appendix B - Measurement setup and automation

Set frequency

Error = mx45SetFrequency(InstrHandle, Frequency)

Description
Sets the frequency of the AC output voltage. Valid values are 16 to 819Hz. If the value exceeds that range, the source is set to the nearest available value.

Inputs
- InstrHandle: Handle to the instrument, obtained from mx45Init
- Frequency: Frequency in Hz

Outputs
- Error
  - 0: no error
  - 1: frequency was not set to desired value

Create arbitrary waveform

WaveFormData = mx45CreateHarmWaveForm(Harmonics)

Description
Creates a 1024 point, 1 cycle waveform that is defined by Harmonics. Harmonics is a 2x50 matrix that defines the harmonic content of the waveform. The first row contains relative amplitudes in %, the second phases in degrees relative to the beginning of the wave (so only relative to the fundamental if that phase is set to 0). The output is scaled to fit [-1, 1]. To upload a waveform to the net simulator, use mx45CreateWaveForm.

Example: Signal = mx45CreateHarmWaveForm([100 0 5 0 ... 0 ; 0 0 90 0 ... 0]) yields a sine wave with 5% 3rd harmonic with phase 90 degrees.

Inputs
- Harmonics: 2x50 matrix that defines the harmonic content of the generated waveform

Outputs
- WaveFormData: Array of 1024 data points that define 1 cycle of the waveform
Appendix B - Measurement setup and automation

Upload waveform

\[
\text{Error} = \text{mx45CreateHarmWaveForm}(\text{InstrHandle}, \text{WaveFormName}, \text{WaveFormData})
\]

**Description**
Uploads an arbitrary waveform to the net simulator memory and gives it the name WaveFormName. The waveform should have exactly 1024 points and should be within \([-1,1]\). Use `mx45CreateHarmWaveForm` to construct the waveform. The memory can contain up to 44 waveforms. When you specify a name that is already present, the waveform will be overwritten.

**Inputs**
- `InstrHandle` Handle to the instrument obtained from `mx45Init`
- `WaveFormName` Name the waveform should receive in the source (text string). Maximum 12 characters and no special characters. Not case sensitive.
- `WaveFormData` Array of 1024 points between -1 and 1 that define 1 cycle of the waveform.

**Outputs**
- `Error`
  - 0: no errors
  - 1: WaveFormName has wrong dimensions, memory is full or waveform has multiple zero crossings. (The latter can lead to trigger problems on the oscilloscope)

Set waveform

\[
\text{Error} = \text{mx45SetWaveForm}(\text{InstrHandle}, \text{Channel}, \text{WaveFormName})
\]

**Description**
Sets the waveform for a specified channel. Use `mx45CreateHarmWaveForm` to upload your waveform.

**Inputs**
- `InstrHandle` Handle to the instrument obtained from `mx45Init`
- `Channel` Channel number. Valid values are 1, 2 or 3. No arrays accepted.
- `WaveFormName` Text string of the waveform name. Not case sensitive.

**Outputs**
- `Error`
  - 0: no errors
  - 1: Waveform was not present on the machine or setting waveform was not successful.

Get waveform names

\[
\text{WaveForms} = \text{mx45GetWaveForms}(\text{InstrHandle})
\]

**Description**
Gets a list of waveforms in the instrument memory.

**Inputs**
- `InstrHandle` Handle to the instrument obtained from `mx45Init`

**Outputs**
- `WaveForms` Array of text strings with waveform names.
Appendix B - Measurement setup and automation

Delete waveform

Error = mX45DelWaveForm(InstrHandle, WaveFormName)

*Description* Deletes a waveform from the instrument memory. You cannot remove 'SINE', 'SQUARE' and 'CLIPPED'.

*Inputs*  
- InstrHandle: Handle to the instrument obtained from mX45Init  
- WaveFormName: Waveform that is to be removed.

*Outputs*  
- Error:  
  - 0: no errors  
  - 1: specified waveform was not present in the memory or you specified sine, square or clipped

Clear waveform memory

Error = mX45ClearWaveForms(InstrHandle)

*Description* Removes all waveforms from the instrument memory except 'SINE', 'SQUARE' and 'CLIPPED'.

*Inputs*  
- InstrHandle: Handle to the instrument obtained from mX45Init

*Outputs*  
- Error:  
  - 0: no errors  
  - 1: there was an error while removing the waveforms

Set source output

Error = mX45SetOutput(InstrHandle, Channel, WaveName, Voltage, CurrentLimit)

*Description* High level function that sets the waveform, voltage and current limit for a specified channel.

*Inputs*  
- InstrHandle: Handle to the instrument obtained from mX45Init  
- Channel: Channel. Valid values are 1, 2 and 3. No arrays accepted  
- WaveName: Text string that defines the waveform  
- Voltage: Voltage in V. Should be within range. See mX45SetACVolt  
- CurrentLimit: Current limit in A. Should be within range. See mX45SetCurrLimit

*Outputs*  
- Error:  
  - 0: no errors  
  - 1: one of the used functions returned and error
B.5.3 Oscilloscope

The Handyscope 3 is designed to be controlled from the computer. It communicates over USB 2.0 and also gets its power from it. In case USB 1.0 is used, the extra PS2 cable should be used as USB 1.0 cannot deliver enough power. Before using the oscilloscope install the drivers that are available from the website (www.tiepie.nl). You might have to repeat this several times the first few times you connect the device to your computer. There appears to be bug there.

A Graphical User Interface can also be downloaded from the website (www.tiepie.nl). The GUI can be used to adjust settings and to view waveforms.

The HS3 also comes with a well documented C library. Matlab can call functions in libraries directly. Before you can load the library and use the routines, download the file hs3dll32.zip from the website and copy the files hs3.dll, tiepie.h, hs3f12.hex, hs3f14.hex, hs3f16.hex, hs3f8.hex to [matlabroot]\bin\win32.

With the Matlab routine hs3measure you can control the oscilloscope. Before you can use it, initialise the instrument with hs3init.

---

**Initialise the HandyScope**

```matlab
Error = hs3init
```

*Description*  
Initialises the instrument. When is fails, try to disconnect and reconnect the oscilloscope. Sometimes the instrument cannot be detected after the computer has been in hibernate.

*Inputs*

*Outputs*  
Error  
0: no errors, initialisation successful
>1: an error occurred. See library documentation for more information
**Appendix B - Measurement setup and automation**

**Perform measurement with the HandyScope**

\[
\text{[time, channel1, channel2]} = \text{h3measure(hs3Setup)}
\]

**Description**
Sets the handyscope to the preferences specified in hs3Setup and returns the recorded signals in arrays.

**Inputs**
hs3Setup
Matlab structure that defines the settings of the instrument. It contains the following fields:
- **sensi** sensitivity of channel 1 in Volts - '0' if channel is to be switched off. Valid values are 0.2, 0.4, 0.8, 2, 4, 8, 20, 40, and 80 (Volts). Note that the range extends from - [range] to + [range]. If the signal exceeds 95% of the range, you are notified.
- **attn1** attenuation of the sensor connected to channel 1.
- **mod1** channel 1 mode. '1' for DC, '0' for AC
- **sens2** sensitivity of channel 2 in Volts - '0' if channel is to be switched off
- **attn2** attenuation of the sensor connected to channel 2
- **mod2** channel 2 mode.
- **trsource** trigger source. '1' for channel 1, '2' for channel 2
- **trlevel** trigger level in Volts
- **trslope** trigger slope. '0' for rising, '1' for falling
- **res** vertical resolution in bit. Possible values are: 8, 10, 12, 14, 16 depending on the sample frequency.
- **fsample** sample frequency in Hz. Not continuously adjustable. Device automatically picks closest available value. (you will be notified)
- **reclength** record length. Maximum 131400 samples.
- **postsamp** number of post trigger samples
- **n** number of successive measurements to be taken. Each measurement is stored in new row in the output arrays.

**Outputs**
- **time** Time base. Matrix of size [n x reclength].
- **channel1** Channel 1 signal, multiplied by attn1. Matrix of size [n x reclength]
- **channel2** Channel 2 signal, multiplied by attn2. Matrix of size [n x reclength]
B.5.4 Current source
The Delta SM3000 power source has an analogue steering input (also see Appendix B.1). It is controlled from the Arbitrary Waveform generator that is in the HandyScope 3. Refer to previous section how to connect and install the handyscope on your computer. The AWG operates independently from the oscilloscope and can deliver voltages from -12 to 12 volts. It has several standard waveforms like sine and square but also a memory for arbitrary waveforms.

Several Matlab routines can be used to control the AWG. The next section gives an overview.

B.5.5 HS3 Arbitrary Waveform Generator Matlab communication routines

Initialise the HandyScope

Error = hS3init  

*Description*  Initialises the instrument. When it fails, try to disconnect and reconnect the oscilloscope. Sometimes the instrument cannot be detected after the computer has been in hibernate.

*Inputs*  

*Outputs*  

<table>
<thead>
<tr>
<th>Error</th>
<th>Description</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no errors, initialisation successful</td>
<td>-</td>
<td>Error</td>
</tr>
<tr>
<td>&gt;1</td>
<td>an error occurred. See library documentation for more information</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Call a function from the hs3 library

Error = callDLL(Function, arg1, arg2)

*Description*  Calls a function from the hs3.dll library (uses matlab callib function). Function should be specified, arg1 and arg2 are voluntary. arg1 and arg2 should have the right formats, like double, uint8, or text string.

*Inputs*  

| Function   | Text string with the name of the function |
| arg1, arg2 | Voluntary arguments. |

*Outputs*  

| Error   | Error value returned by the function |

Switch on the output

hS3AWGOn

*Description*  Switches the output of the AWG to on

*Inputs*  

*Outputs*  

-
Appendix B - Measurement setup and automation

Switch off the output

\texttt{hs3AWGOff}

\textit{Description} \quad Switches the output of the AWG to off

\textit{Inputs} \quad -

\textit{Outputs} \quad -

Set the signal type

\texttt{hs3SetAWGSignalType(SignalType)}

\textit{Description} \quad Sets the signal type of the AWG

\textit{Inputs} \quad \textit{Signal Type} 0: Sine  
1: Triangle  
2: Square  
3: DC  
4: Noise  
5: Arbitrary signal (from memory)

\textit{Outputs} \quad -

Create an arbitrary waveform

\texttt{WaveformData = hs3CreateHarmWaveForm(Harmonics)}

\textit{Description} \quad Creates a 1024 point array that contains one cycle of the waveform defined in Harmonics. The values are adjusted to fit \([0, 2^{16}]\). Use \texttt{hs3UploadWaveForm} to upload the waveform to the AWG memory.

\textit{Inputs} \quad \textit{Harmonics} \quad See \texttt{mx45CreateHarmWaveForm}

\textit{Outputs} \quad \textit{WaveformData} \quad 1024 point waveform with values between \([0, 16^{16}]\)

Upload an arbitrary waveform

\texttt{hs3UploadWaveForm(WaveformData)}

\textit{Description} \quad Uploads a waveform to the AWG memory. Only one waveform can be stored at the time. Use \texttt{hs3CreateHarmWaveForm} to create a waveform.

\textit{Inputs} \quad \textit{WaveformData} \quad Waveform. See \texttt{hs3CreateHarmWaveForm}

\textit{Outputs} \quad -
Appendix B - Measurement setup and automation

---

### Set frequency

**hs3SetAWGFrequency(Frequency)**

**Description**
Sets the AWG frequency.

**Inputs**
- Frequency
  - Frequency in Hz

**Outputs**
- 

### Set Amplitude

**hs3SetAWGAmplitude(Amplitude)**

**Description**
Sets the AWG amplitude. Valid values are [0,12]. The amplitude actually is the full scale voltage, so it defines the maximum value of the waveform, not the RMS value. When the signal type is DC (see **hs3SetAWGSignalType**), the amplitude defines the output voltage and the **Offset** (see **hs3SetAWGOffset**) the polarity.

**Inputs**
- Amplitude
  - Amplitude in V

**Outputs**
- 

### Set offset voltage

**hs3SetAWGOffset(Offset)**

**Description**
Sets the offset value of the AWG. When the AWG is in DC mode, it defines the polarity of the output voltage. If Offset > 0 then \( V_{dc} = +\text{amplitude} \) otherwise \( V_{dc} = -\text{amplitude} \).

**Inputs**
- Offset
  - Offset in V

**Outputs**
- 

### Set DC voltage

**hs3SetDCVolt(Voltage)**

**Description**
Sets the AWG so it generates a DC voltage on the output. Valid values are [-12,12].

**Inputs**
- Voltage
  - DC voltage in V. Valid values are [-12,12].

**Outputs**
- 

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Appendix B - Measurement setup and automation

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**Sweep the DC voltage**

```hs3AWGDCSweep(Vstart, Vend, deltaT, Steps)```

**Description**
Generates a stepped DC voltage on the output of the generator. This routine is not suitable for quick DC sweeps. Use a triangle waveform with a low frequency instead.

**Inputs**
- **Vstart**: Start voltage in V. Range = [-12, 12].
- **Vend**: End voltage in V. Range = [-12, 12].
- **deltaT**: Sweep time in s.
- **Steps**: Number of steps from start to end.

**Outputs**
-
HARMONIC MODELLING OF SOLAR INVERTERS AND THEIR INTERACTION WITH THE DISTRIBUTION GRID

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ABSTRACT

Excessive harmonic distortion has been reported in some distribution grids with a high number of photovoltaic inverters. In this paper, a simple model is introduced to describe the interaction between grid components and groups of inverters which can lead to amplification of harmonic voltages. The model is validated by using extensive measurements for several types of commercially available photovoltaic inverters. The measurement setup and method are described and the results are presented.

INTRODUCTION

Government promotion of renewable energy sources has led to several large scale solar power plants in the Netherlands. In those installations, a large amount of relatively low power inverters is connected to a common AC low voltage bus and high voltage distortion levels have been reported although the single inverters comply to the harmonic emission standard [1]. Several methods have been proposed in literature ([2], [3], [4]) to predict the harmonic distortion caused by a large number of photovoltaic inverters. This paper focuses on the interaction between the inverters and the distribution grid which appears to be at the origin of problems.

Experiments presented in this paper show that a distorted grid voltage can significantly influence the harmonic content of the current injected by the inverter. This interaction can lead to amplification of harmonic voltages or resonances between network components and (groups) of inverters. These effects are not included in present harmonic emission standards.

In [5] a simple model has been proposed to model grid - inverter interaction with standard grid components. The objective of this paper is to validate the model for several commercial photovoltaic inverters. The proposed model, the measurement strategy and setup are discussed in detail and measurement results are presented.

PROPOSED INVERTER MODEL

Figure 1 shows the proposed inverter model connected to the distribution grid. All components are frequency dependent (indicated by the harmonic number (n) in brackets). The model consists of a current source (I_n) that models the injected harmonic current when the terminal voltage (V) is undistorted, and an admittance (Y) that models the interaction between harmonic voltages in the grid and the injected harmonic current (I). The grid is modelled as an ideal voltage source (U_{grid}) and a series impedance (Z).

\[ I_n = I_{in} + I_Y \]  
\[ I_Y = Y \cdot V_n \]  
\[ I = \sum I_n \quad V = \sum V_n \]

(1) (2) (3)

where subscript n indicates the harmonic frequency.

Modelling groups of inverters

Figure 2 shows a model of a power electronic load (f.e. a computer), a linear load (f.e. classic light bulbs) and a PV inverter connected along a cable. The linear load is only modelled as a frequency dependent admittance as it does not inject harmonic current in an undistorted grid. Power electronics are active devices and consequently the model conductance (real part of Y) can be negative. The electric circuit is then only damped by the cable and grid impedance and linear loads. In grids with high penetration of power electronic devices such as solar plants the damping is low and significant amplification of harmonic voltages can
occur. Resonances between grid reactance and (groups) of power electronic devices are also possible. As the model components are frequency dependent, the number of resonances can increase or decrease compared to the same circuit with frequency independent components. When the influence of the cable impedance between loads is negligible, all admittances and current sources can be added to form one model. This reduces the calculation time in a grid simulation. Additionally a harmonic model for a typical household could be obtained.

**Frequency decoupling** - In linear systems, frequencies are decoupled, i.e. the $n^{th}$ harmonic voltage only affects the $n^{th}$ harmonic current. This property was already used in equations 1 to 3.

**Influence of operating power** - Due to variations in irradiation of the photovoltaic generator the operating power of the inverter will change over time. The operating power influences the injected harmonic current and consequently the value of the current source and the admittance in the model.

These properties form the basis for the model validation discussed in the next sections.

**MEASUREMENT STRATEGY & SETUP**

A test setup (Figure 4) has been constructed to test photovoltaic inverters with a power range of up to 3kW.

![Figure 4 Measurement setup](image)

A hardware photovoltaic simulator provides stable and adjustable DC input conditions. It consists of a fast current source and strings of power diodes. A grid simulator generates a grid voltage with adjustable harmonic distortion. An oscilloscope records voltage and current at the inverter terminals to determine the harmonic distortion. A PC governs the automated measurement process.

Figure 5 shows a flow chart of the measurement strategy. The harmonic current distortion is measured in an undistorted grid. Then, the grid voltage is distorted with one harmonic voltage of certain amplitude and phase. In successive measurements amplitude and phase are changed over a range of values. The measurements are repeated for different harmonics. To determine the influence of operating power the measurements are repeated with other PV simulator settings.

Linear regression is used to determine model parameters $I_0$ and $Y$ for each harmonic frequency ($I_0$ is the offset and $Y$ the gradient $dI/dV$). The RMSE (root mean square error) of the regression is an indication of how well the model describes the harmonic current from the inverter.

**Figure 3 Illustration of linear relation between harmonic voltage and current**
Switch on inverter

Undistorted grid

Measure V, I at inverter terminals and save to disk

Add 1st harmonic to grid voltage

Measure V, I at inverter terminals and save to disk

Change amplitude of harmonic voltage

Last amplitude?

YES

NO

Last harmonic?

YES

NO

Last phase?

YES

NO

Go to next harmonic

Switch off inverter

Data post processing

Figure 5 Measurement strategy

MEASUREMENT RESULTS

Four commercially available inverters have been tested. Table 1 shows properties of the inverters presented in this paper. An overview of common photovoltaic inverter topologies can be found in [6] and [7].

Table 1 inverter properties

<table>
<thead>
<tr>
<th>Inverter</th>
<th>Topology</th>
<th>( P_{\text{Nom}} )</th>
<th>THD(_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HF transformer</td>
<td>110W</td>
<td>5.6%</td>
</tr>
<tr>
<td>2</td>
<td>HF transformer</td>
<td>850W</td>
<td>1.9%</td>
</tr>
<tr>
<td>3</td>
<td>LF transformer</td>
<td>1500W</td>
<td>4.5%</td>
</tr>
<tr>
<td>4</td>
<td>Transformerless</td>
<td>1500W</td>
<td>21.7%</td>
</tr>
</tbody>
</table>

Harmonic distortion in an undistorted grid

Table 1 shows that the THD\(_1\) of inverters 1, 2 and 3 in an undistorted grid is low. \( I_o \) is therefore small for all frequencies. Inverter 4 injects considerable 3rd and 5th harmonics. Figure 6 shows current waveforms of inverter 2 and 4. The difference in harmonic distortion is easy to see.

![Figure 6 Inverter 2 and 4 current in an undistorted grid](image)

**Linearity**

Figure 7 shows measurement results for inverter 1 operated at 70% of nominal power. A 3rd harmonic voltage was added to an undistorted grid; its amplitude was changed over values \([0, 0.5, ..., 5]\)% and its phase over \([0, 30, ..., 330]\)°. The measured 3rd harmonic current for each set point is depicted in the complex plane (\(O' = \text{origin}\)). Points with an asterisk indicate set points where the phase angle of the harmonic voltage was equal to zero. Phase angles of other set points can then be derived.

![Figure 7 Inverter 1 measurement results for \(n = 3\)](image)

![Figure 8 Inverter 2 measurement results for \(n = 5\)](image)
In addition, in Figure 7 phasors I_x, I_y and I are drawn for a set point where the harmonic voltage was 4%, 270°. The harmonic current measurements form the same star-like shape in the complex plane as the harmonic voltage settings (not shown here), and this indicates a linear relation between harmonic voltage and current. Figure 8 shows the 5th harmonic current for inverter 2, operated at 100% of its nominal power. For this device, the relation between harmonic voltage and current is less linear.

**Frequency decoupling**

Figure 9 shows the influence of the 3rd harmonic voltage on harmonic currents from the 2nd to the 50th. The vertical axis is the standard deviation of all current measurements where a 3rd harmonic voltage was added to the undistorted grid. The influence on other harmonic currents than the 3rd is small and consequently the error introduced by assuming frequency decoupling is small. The actual error that is introduced is not straightforward to quantify as it depends on the amplitude of the harmonic voltage. Figure 10 shows the influence of the 15th harmonic voltage on all harmonic currents up to the 50th for inverter 3. Here, considerable low (even and odd) harmonic currents are evoked which are in the order of 1/3 the amplitude of the same currents in an undistorted grid. The error introduced by assuming frequency decoupling is thus significant.

![Figure 9 Inverter 1 frequency decoupling](image9)

![Figure 10 Inverter 3 frequency decoupling](image10)

**Model parameters**

Figure 11 shows model components G and C for inverter 1, for several harmonic frequencies and two power levels (* = 70%, * = 35% of P_{nom}). G is negative for lower and positive for higher frequencies. C is more or less constant. When the operating power is decreased, G increases and C decreases. The RMSE of the model is low, below 0.2% of the fundamental current for all harmonic frequencies.

![Figure 11 Inverter 1 model component values for 70% (*) and 35% (*) of P_{nom}](image11)

![Figure 12 Inverter 2 model component values for 100% (*) and 50% (*) of P_{nom}](image12)

![Figure 13 Inverter 3 model component values](image13)

**Even and odd harmonics**

In [1] it was assumed that the inverters behave similarly for even and odd harmonics. The measurements performed within this research however show that this is not the case. Most inverters are far less linear for even harmonics and the component values are very different. Component values found for even harmonics can therefore not be used to estimate those for odd harmonics.
Parallel devices
When multiple devices are connected in parallel, the model assumes that components can be added. Measurements show that this is indeed the case.

CONCLUSIONS

A model to predict the harmonic distortion generated by power electronic converters in a distorted distribution grid has been discussed and validated for several types of commercially available photovoltaic inverters. The model consists of a frequency dependent current source and admittance, represented by a conductance and a capacitance. The model assumes a linear relation between harmonic voltage and harmonic current at the inverter terminals and no influence between different harmonic frequencies.

Extensive experiments have shown that the model can indeed predict the harmonic current rather accurately. The model conductance depends on frequency and can be both negative and positive. The model capacitance is constant with frequency. The reactive current through the capacitance is large compared to the active current through the conductance and it increases with frequency. Consequently, the inverter can be modelled as a capacitance for frequencies higher than approximately $n=15$. Amplification of harmonic grid voltages is thus expected to mainly occur due to resonances between the grid reactance and the capacitance of groups of inverters and to a lesser extent due to a negative conductance.

The model capacitance is in the order of several µF for a 1 kW inverter, but there is no fixed relation between capacitance and nominal power of the inverter. When the operating power is decrease, the capacitance decreases as well (the relation is not proportional). Consequently, resonances in the grid depend on the irradiation of the photovoltaic generators. The measured capacitance is probably the effective sum of the physical capacitor at the inverter AC terminals and the capacitive behaviour of the control circuit. This could explain the influence of the operating power.

Future research will focus on investigating the relation to operating power in more detail and the practicability of the model in grids with a large number of inverters. Additionally, the model will be validated for other types of power electronic devices such as switch mode power supplies.

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