

**Estimation of the potential to pollute the electricity
network with harmonics due to the use of small
micro generators with inverters**

Measurement of the Complex Conductance,
an additional test method for inverters

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PREFACE

In this document a method to estimate the potential to pollute the electricity network with harmonics due to large scale implementation of small grid connected micro generators with inverters, like photovoltaics, is laid down. The method is called the 'Complex Conductance Measurement Method'. Although this method is written for inverters of small grid connected micro generators, it can be applied for all kinds of loads. This document has been written to provide input for NTA 8494 [1] (Netherlands Technical Agreement), a guideline for inverter testing, and to provide input to the Nederlands Elektrotechnisch Comité (NEC82) [2], the Netherlands National Committee for Solar energy systems of the: International Electro technical Commission (IEC) and the European Committee for Electro technical Standardization (CENELEC).

At various phases the Complex Conductance Measurement Method was presented to members of the NEC 82 and other experts in the field of photovoltaic systems and components. Their comments and suggestions have contributed to this Complex Conductance Measurement Method for both structure and technical contents.

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ABSTRACT

Currently the total power of PV-generators in the built environment is small compared to the power of the distribution transformer. With the steady growth of PV installations, the penetration of PV-generators in the built environment will grow as well. This will lead to new phenomena, which may eventually result in grid instabilities [3]. In order to be able to predict whether these phenomena will occur, a simple though accurate harmonics model for the grid, the cables the loads and the inverters is presented, as well as a measuring method to determine the necessary frequency dependent parameters of inverters and loads in general.

In a previous project [4] a preliminary harmonic interaction test method for inverters was proposed, this result was an important input for this project.

This project focuses on harmonic pollution of the grid voltage at large-scale implementation of small grid connected micro generators with inverters, like photovoltaics. The goal of this project is to lay down a test method to qualify inverters on this subject. The upper lying target is to contribute to a new standard on inverter testing, NTA 8494 [1] (Netherlands Technical Agreement), a guideline for inverter testing.

In the first part of this report the 'Complex Conductance Measurement Method' has been critically reviewed both theoretically and practically. In the second part of this report the 'Complex Conductance Measurement Method' has been adapted to situations in practice. With the latter method a few measurement examples are presented and discussed.

The measuring method described in this report can be used to determine the frequency dependent parameters of inverters and loads. The results depend strongly on the inverter topology. Negative values for the normalized conductance appear to be possible for some types of inverters. As this may result in grid instabilities, inverters with negative conductance should only be used in projects with large-scale implementation of PV when sufficient compensation is available.

Results of the mentioned Measurement Method can easily be used in a more complex simulation to predict the level of harmonic distortion and the possibility of resonance-effects.

From the experiments can be remarked that a further research on the behaviour of different kinds of loads in relation to harmonics is needed to get familiar with test results.

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1 INTRODUCTION

Currently the total power of PV-generators in the built environment is small compared to the power of the distribution transformer. With the steady growth of PV installations, the penetration of PV-generators in the built environment will grow as well. This will lead to new phenomena, which may eventually result in grid instabilities. In order to be able to predict whether these phenomena will occur, a simple though accurate harmonics model for the grid, the cables the loads and the inverters is presented, as well as a measuring method to determine the frequency dependent parameters of inverters and loads in general.

In a previous project [4] a preliminary harmonic interaction test method for inverters was proposed, this result was an important input for this project.

This project focuses on harmonic current emission of small grid connected micro generators with inverters, like photovoltaic. The goal of this project is to lay down a test method to qualify inverters on this subject. The upper target is to contribute to a new standard on inverter testing, NTA 8494 [1] (Netherlands Technical Agreement), a guideline for inverter testing.

2 COMPLEX CONDUCTANCE MEASUREMENT THEORY

Analysing harmonics in a LV- and MV-grid and thereby considering not linear loads and grid-connected PV-systems is difficult due to the interaction between the different components. Furthermore the characteristics of most components depend on frequency. To make a proper estimation of a possible harmonic problem the following issues are described in this chapter.

- Modelling of the grid, network cabling, load and inverters.
- Instability analysis of the modelled system
- Characteristic description of the components

2.1 Modelling

In practice many loads and multiple PV-inverters are connected to the grid. The simplest model of a grid connected PV-system consist of a grid connected to a single load and a single inverter as shown in Figure 1.

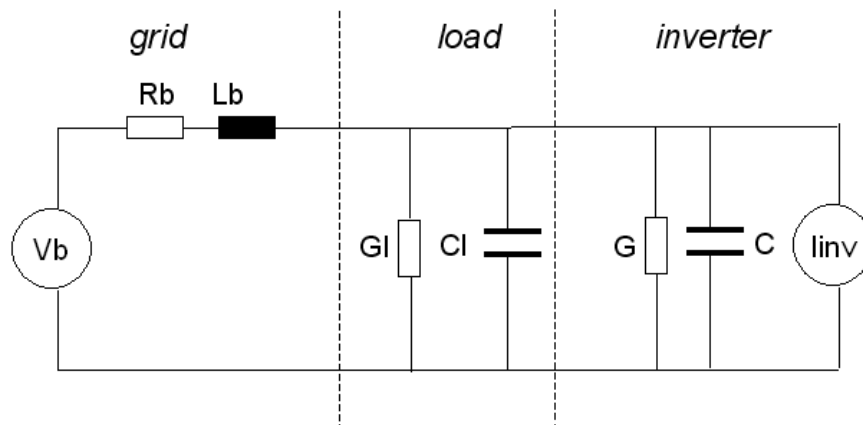


Figure 1 Simple model of grid-connected PV-system

The load is modelled as a complex conductance $Y_{load} = G_{load} + j\omega C_{load}$. Both G_{load} and C_{load} may vary with the frequency. The grid consists of:

- A harmonic voltage source modelling the voltage background harmonic distortion
- The resistance of (mostly) the LV-cable, depending on frequency due to the skin- and proximity effect
- The inductance of the cable and MV/LV-transformer

The inverter is modelled with:

- A harmonic current source, modelling the harmonic currents of the inverter without the effect on background voltage distortion from the grid
- The capacitor of the inverter which can be calculated by measuring the imaginary part of the power on the connection point of the inverter
- The conductance of the inverter which can be calculated by measuring the real part of the power on the connection point of the inverter

To study the behaviour of the model in the frequency domain we can add the capacitors and conductances of the load and the inverter to get the model of Figure 2.

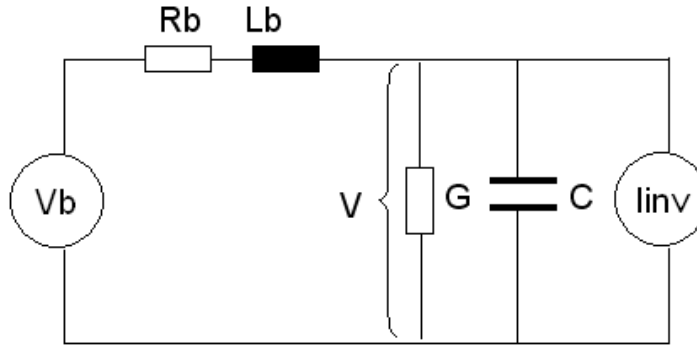


Figure 2 Model with combined capacitors and conductances

The transfer function of this circuit is given by the following equation:

$$V = \frac{V_b + I_{inv}(R_b + j\omega L_b)}{1 + (R_b + j\omega L_b) \cdot (G + j\omega C)} \quad (1)$$

- V_b = the grid background harmonic voltage distortion
- V = the harmonic voltage at the Point of Common Coupling (PCC)
- R_b = the grid resistance, including the influence of the skin-effect
- L_b = the grid inductance
- I_{inv} = the harmonic current injected by the inverter (without background distortion)
- C = the total capacitor (sum of load and inverter capacity)
- G = the total conductance (sum of load and inverter conductance)

2.1.1 Instability analysis

This system will become unstable when the denominator of the transfer function (1) becomes near zero. This will take place when:

$$G = -\frac{R_b}{Z_0^2} \quad (2) \quad \text{and} \quad \omega = \omega_0 \sqrt{1 - \left(\frac{R_b}{Z_0}\right)^2} \quad (3)$$

In these equations the common definitions $Z_0 = \sqrt{\frac{L_b}{C}}$ and $\omega_0 = \frac{1}{\sqrt{L_b C}}$ are used.

Instability will take place at the resonance frequency as the dissipation in the series resistor R_b equals the power delivered by the negative conductor G .

The quality factor of this resonance circuit can be defined as:

$$Q = \frac{Z_0}{R_b + G \cdot Z_0^2} \quad (4)$$

Total instability can only take place for negative values of G. However, for low values of $R_b + G \cdot Z_0^2$ significant amplification of harmonics may occur.

An example with the amplification of the harmonic voltages at the PCC (value of V) is given below. The following practical values of the different components, background voltage and inverter harmonic current were used.

Example 1:

V_b	= 5 V, the grid background harmonic voltage distortion
V	= the harmonic voltage at the PCC (connection point load and inverter)
R_b	= 0.2 Ω , the grid resistance (at 50 Hz)
L_b	= $1.11 \cdot 10^{-4}$ H, the grid inductance
I_{inv}	= 1A, the harmonic current injected by the inverter
C	= $50 \cdot 10^{-6}$ F, the total capacitor (sum of load and inverter capacity)

Instability can occur in very specific circumstances. Due to the skin- and proximity-effect the resistance of the grid is related to frequency and therefore the resonance frequency depends extra on this resistance.

The G for instability in example 1 is shown in Figure 3 and is in the range of –0.1 S and –0.7 S (S stands for siemens). The R_b influences the resonance frequency in such a way that at a higher frequency the G for instability is lower.

Figure 4 shows that with a G of –0.6 S in example 1, the resonance frequency will be around 1450 Hz. For total instability the G with this frequency should be –0.42 S as shown in Figure 3.

In Figure 5 the voltage at the PCC in example 1, is presented with a G of –0.6 S, -0.25 S and 0.15 S. Figure 5 shows that indeed there is a resonance frequency of 1450 Hz and a large amplification of the harmonic voltage due to the fact that the G is close to –0.42 S.

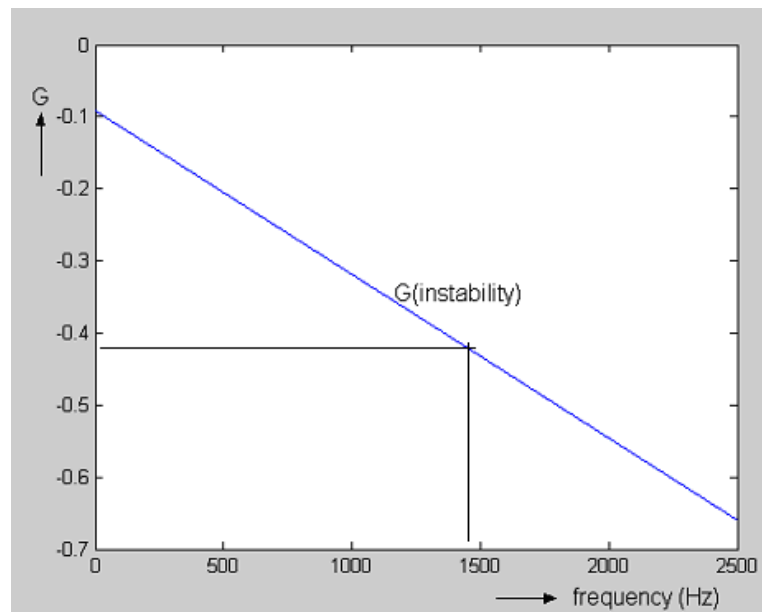


Figure 3 $G(S)$ leading to instability in example 1

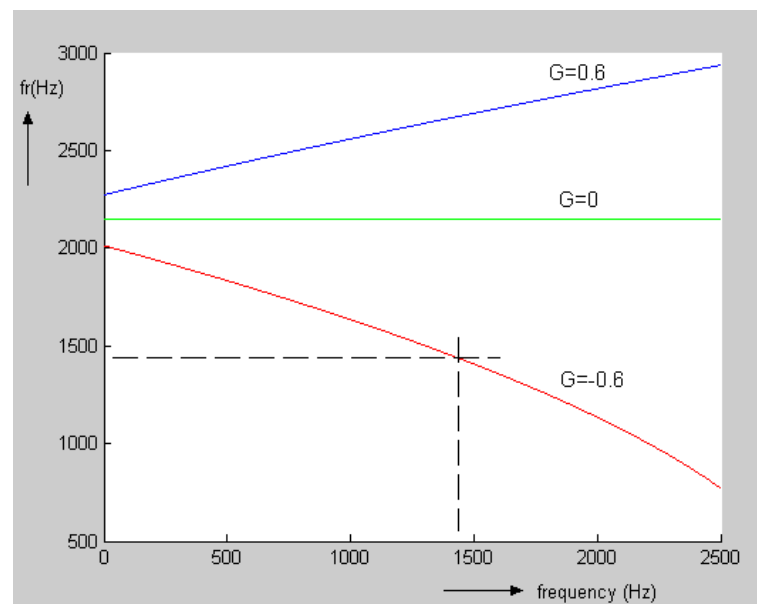


Figure 4 Relation between $G(S)$ and resonance frequency in example 1

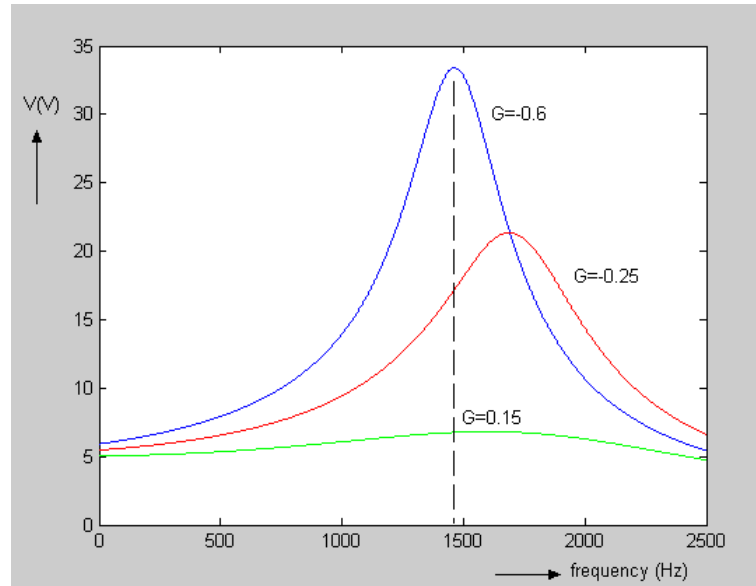


Figure 5 Amplification of the harmonic voltage in relation to G (S) for example 1

Instability will only take place during the special conditions when G meets the requirements in equation (2), at the resonance frequency which can be calculated with equation (3). To estimate the occurrence of this problem we need to know more about:

- R_b , the resistance of the grid, including the influence of the skin-effect
- L_b , the inductance of the grid, including transformer and cables
- G_{inv} , the conductance of the inverter
- G_{load} , the conductance of the load
- I_{inv} , the harmonic current of the inverter
- C_{inv} , the capacity of the inverter
- C_{load} , the capacity of the load
- V_b , the background harmonic voltage.

2.2 Component characteristics

Calculations can only be made when the characteristics of all components are available. This includes the parameters of the grid, the inverters and the loads.

2.2.1 Grid parameters

2.2.1.1 Cable and transformer

The resistance of the grid is mainly the resistance of the cables. The resistance of cables is due to the proximity- and skin-effect related to the frequency. To get a realistic view on the impedance of a low-voltage cable in relation with the frequency, the resistance is plotted in Figure 6 for several cables. Keeping in mind that almost every low voltage customer is

connected with the grid with a separate connection cable with a standard length of 12 m and a cross section area of 10 mm², a minimum resistance of proximally 0.05 Ω will always exist.

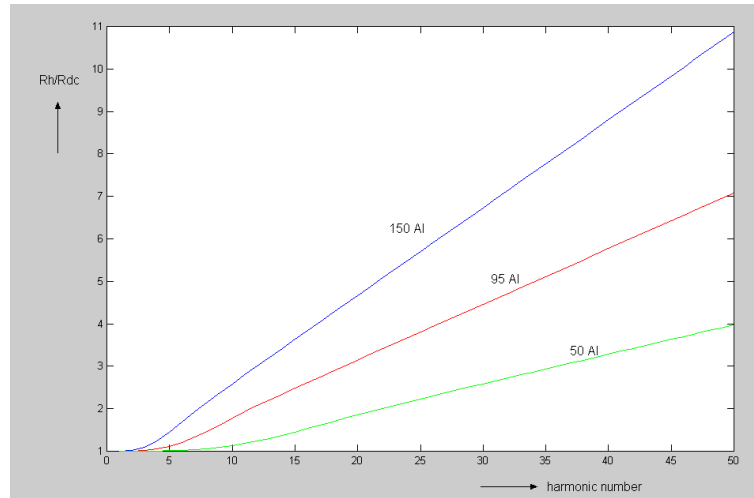


Figure 6 Resistance of three low-voltage cables in relation with the frequency

Depending on the way the inverters are connected to the grid a wide range of values for R_b can occur. Figure 7 shows the minimum and maximum values in relation to the frequency.

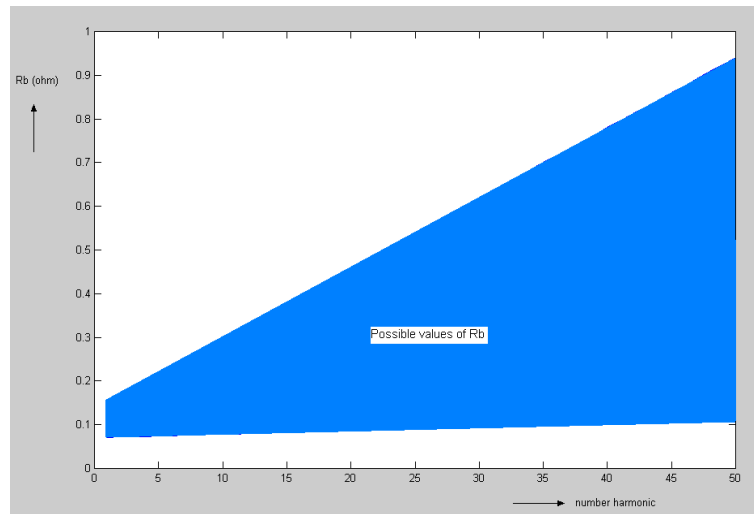


Figure 7 Possible values of R_b

The inductive resistance of the grid is depending of the transformer and the length of the low-voltage cables. For both the transformer as the low voltage cables the 50 Hz impedances can be found in the datasheets of the manufacturer. The inductive impedance of the most common used transformers is within a range of 10 to 30 m Ω . For the cables the inductive impedance is around 80m Ω /km. When we assume that the length of the cable can be within the range of 50 to 400 m then L_b will be in the range of $0.4 \cdot 10^{-4}$ and $2 \cdot 10^{-4}$ H.

2.2.1.2 Background distortion of harmonic voltages in the network

In the Dutch situation a national program of power-quality measurements (PQ-measurements) is made during 5 years [5]. From the results of this program average background harmonic voltages can be calculated. Of course this is a general average for the system and does not give specific information about the harmonic voltage on a specific Point of Common Coupling (PCC). Table 1 and Table 2 give these average harmonic voltages for low- and medium voltage level. With the 95%-value in the tables is meant 95% of the 10 min. mean rms values of the supply voltage, this is according to the EN 50160 [6].

Table 1 Average harmonic background voltage in the LV-grid

harmonic number	Limit EN 50160	Average 95%-value	Standard deviation	Highest 95%-value
THD	8%	2.98	0.75	5.16
2	2.0%	0.03	0.02	0.21
3	5.0%	0.64	0.41	1.98
4	1.0%	0.01	0.02	0.16
5	6.0%	2.50	0.94	5.03
6	0.5%	0.01	0.01	0.13
7	5.0%	1.44	0.42	2.71
8	0.5%	0.00	0.01	0.05
9	1.5%	0.26	0.20	1.04
10	0.5%	0.00	0.01	0.04
11	3.5%	0.43	0.18	0.94
12	0.5%	0.00	0.00	0.04
13	3.0%	0.29	0.15	0.77
14	0.5%	0.00	0.01	0.05
15	0.5%	0.08	0.10	0.56
16	0.5%	0.00	0.01	0.05
17	2.0%	0.05	0.06	0.34
18	0.5%	0.00	0.01	0.05
19	1.5%	0.09	0.09	0.58
20	0.5%	0.00	0.00	0.05
21	0.5%	0.08	0.07	0.30
22	0.5%	0.00	0.00	0.05
23	1.5%	0.05	0.05	0.23
24	0.5%	0.00	0.00	0.04
25	1.5%	0.04	0.04	0.20

Table 2 Average harmonic background voltage in the MV-grid

harmonic number	Limit EN 50160	Average 95%-value	Standard deviation	Highest 95%-value
THD	8%	2.43	0.61	3.99
2	2.0%	0.03	0.02	0.12
3	5.0%	0.16	0.12	0.82
4	1.0%	0.01	0.02	0.09
5	6.0%	2.24	0.67	3.44
6	0.5%	0.02	0.04	0.17
7	5.0%	1.21	0.58	2.75
8	0.5%	0.01	0.02	0.08
9	1.5%	0.02	0.03	0.10
10	0.5%	0.01	0.02	0.05
11	3.5%	0.38	0.13	0.66
12	0.5%	0.01	0.02	0.08
13	3.0%	0.25	0.12	0.54
14	0.5%	0.01	0.01	0.05
15	0.5%	0.00	0.00	0.03
16	0.5%	0.00	0.01	0.06
17	2.0%	0.03	0.02	0.10
18	0.5%	0.01	0.01	0.10
19	1.5%	0.03	0.02	0.13
20	0.5%	0.00	0.01	0.02
21	0.5%	0.00	0.01	0.03
22	0.5%	0.00	0.01	0.03
23	1.5%	0.01	0.02	0.10
24	0.5%	0.00	0.00	0.02
25	1.5%	0.00	0.01	0.04

2.2.2 Inverter parameters

The inverter parameters can be measured by means of a harmonic power analyser and two AC-power sources in series. The circuit is shown in Figure 8.

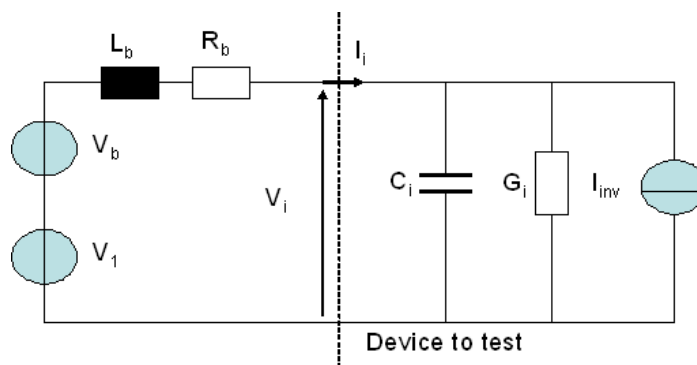


Figure 8 Test circuit for harmonic analysis

The first voltage source V_1 creates the nominal grid voltage and frequency to bias the inverter in its proper working area. The second voltage source V_b will be used to inject harmonics. The series impedances represent the total output impedance of both voltage sources. The parallel connection of the capacitor, conductor and current source represents the inverter. The current I_i and voltage V_i are measured by the harmonic analyser which determines the voltage, current,

active and reactive power of the inverter for the fundamental and the harmonics. Note the definition of the polarity: Positive power means that power delivered by the voltage sources is dissipated in the inverter.

The measurement is done as follows:

- First V_b is set to zero. The inverter power is set to nominal power. Now all the harmonic current (I_{inv}) can be measured.
- Secondly V_b is set to the first harmonic of which the current measured during step 1 was below 0.1% of the fundamental current. The level of V_b is set to, for example, 2 or 3%. The voltage, current, active and reactive powers are measured or calculated. Now the normalized conductance and capacitance of the injected harmonic can be calculated with:

$$G_{i(n)} = \frac{P_{i(n)}}{V_{b(n)}^2} \quad \text{and} \quad C_{i(n)} = \frac{-Q_{i(n)}}{n \cdot \omega \cdot V_{b(n)}^2}$$

- The measurement of step 2 is repeated for all harmonics of which the injected harmonics under step 1 was smaller than 0.1% of the fundamental current.

Note: per definition a component value is positive, in order to obtain a positive value of the capacitance at capacitive loads, a negative sign has been added to the reactive power $Q_{i(n)}$ (reactive power is negative at capacitive loads). If the measurement give a negative $C_{i(n)}$, the result must be seen as an inductance.

Instead of the absolute value of G_i and C_i it is more practical to work with a normalized value. Therefore G_i will be divided by G_{ref} , which is defined as the value of a conductor that would dissipate the nominal inverter power when the inverter is connected to the nominal grid voltage at fundamental frequency.

This gives:

$$G_{ref} = \frac{|P_{inv,nom}|}{V_{nom}^2}$$

Note: G_{ref} is mainly used to scale and should be therefore desirable always positive. P_{nom} for an inverter is negative and P_{nom} for dissipating loads like a resistor is positive. $|P_{nom}|$ is always positive. To achieve always a positive G_{ref} , the modulus of $|P_{nom}|$ has been taken.

The normalized inverter conductance for the n^{th} harmonic can be calculated with:

$$\frac{G_{i(n)}}{G_{ref}} = \frac{P_{i(n)} \cdot V_{nom}^2}{V_{b(n)}^2 \cdot |P_{nom}|}$$

Similar to above it is also more practical to use a normalized value of the capacitance. Therefore C_i will be divided by C_{ref} , which is defined as the value of the capacitor that would carry the same current as the inverter at nominal power.

This gives:

$$C_{ref} = \frac{|P_{inv,nom}|}{\omega \cdot V_{nom}^2}$$

Note: To achieve always a positive C_{ref} , the modulus of $|P_{nom}|$ has been taken.

Using the relation: $C_{i(n)} = \frac{-Q_{i(n)}}{n \cdot \omega \cdot V_{i(n)}^2}$ the normalized value for C_i can be written as:

$$\frac{C_{i(n)}}{C_{ref}} = \frac{-Q_{i(n)} \cdot V_{nom}^2}{n \cdot V_{b(n)}^2 \cdot |P_{nom}|}$$

Note: C_{ref} and G_{ref} depend on the nominal grid voltage and frequency.

To ease calculations on a 50Hz/230V grid, the following formulas can be used to calculate the reference quantities C_{ref} and G_{ref} of an inverter by multiplying the outcome of the formulas with the modules of the nominal output power $|P_{nom}|$ of the inverter:

$$\frac{C_{ref}}{|P_{nom}|} = \frac{1}{\omega \cdot V_{nom}^2} = \frac{1}{2 \cdot \pi \cdot 50 \cdot 230^2} = 60 \frac{nF}{W}$$

and

$$\frac{G_{ref}}{|P_{nom}|} = \frac{1}{V_{nom}^2} = 18.9 \frac{\mu S}{W}$$

The same measurement procedure as described for inverter can be used to measure the load parameters for different kind of loads.

3 COMPLEX CONDUCTANCE MEASUREMENT INTO PRACTICE

During this Complex Conductance Measurement the first 50 harmonics were examined on a passive network of a resistor and a capacitor in parallel and also on two small single-phase PV inverters with an output power less then 300W.

3.1 Procedure

The measurements were done under laboratory conditions with the use of a grid simulator and a harmonic power analyser. To let the grid simulator fit in with situations in practice, output impedance was added. This added impedance will also ease the requirements of the grid simulator. The grid impedance was build out of a resistor in series with an inductor and was chosen according to IEC 60725 [1]. Table 3 gives an overview of the resistor and inductor values for the phase and neutral feeder.

Table 3 An overview of the grid impedance

grid impedance @ 50Hz, according to IEC 60725	
phase	$0.244\Omega + j\ 0.153\Omega$
neutral	$0.160\Omega + j\ 0.104\Omega$

To avoid damage to the Device Under Test (DUT) it is important to choose the grid impedance in a way that resonance's between the DUT's output impedance and the grid simulator impedance will not resonate in the range up to the 50th harmonic, this because the forced excitation with harmonic voltages during the measurements can lead to excessive currents in a resonance peak.

During the measurements the inverters were working just below their maximum power to avoid influences due to saturation phenomena.

The grid simulator was driven by a personal computer with special wave-shape software, with this very easily harmonics can be added to the fundamental.

The measurement procedure that was followed in practice is:

1. Let the grid simulator produce a wave shape without harmonic voltage pollution. Measure Voltage, Current and Power on a working DUT for the fundamental and all harmonics up to the 50th.
2. Select all even harmonics with a current of maximum 0.1% of the fundamental current.
3. Test the DUT successively with the fundamental added with only one of the selected even harmonic at one time. Select the amplitude of the added harmonic from Table 5 below.

Table 4 Amplitude of the added harmonic voltage

harmonic number	harmonic amplitude	phase angle
2 tot 10	3.0 %	0°
10 tot 20	2.5 %	0°
20 tot 30	2.0 %	0°
30 tot 40	1.5 %	0°
40 tot 50	1.0 %	0°

4. Measure up to the 50th harmonic, successively for each selected harmonic at the time, the following quantities:
 - Voltage
 - Current
 - Phase angle between Voltage and Current
 - Power
 on a working device under test (DUT).
5. Calculate for each measurement with harmonic (n) the following:

$$I / I_{\text{ref}} = I_{n0} \cdot U_{\text{ref}} / |P_{\text{ref}}|$$

$$G_n / G_{\text{ref}} = (U_{\text{ref}})^2 \cdot P_n / ((U_n)^2 \cdot |P_{\text{ref}}|)$$

$$C_n / C_{\text{ref}} = (U_{\text{ref}})^2 \cdot (-P_n \cdot \tan \varphi_n) / ((U_n)^2 \cdot |P_{\text{ref}}| \cdot n).$$

6. Present these calculated values and write them into three graphics (I / I_{ref} , G_n / G_{ref} and C_n / C_{ref}) with the values as function of the harmonic numbers, starting with the second harmonic (n=2).

3.1.1 Quantities in practice

U_{ref} [V] the RMS value of the nominal grid voltage, for example: 230V.

I_{ref} [A] the RMS value of the current at P_{ref} .

P_{ref} [W] the nominal delivered or dissipated active AC-power according to the manufacturer specification. P_{ref} is different for the operating modus of a device, for example at the examination of a device in the stand-by mode, the active AC-power in this mode should be used. At PV string-inverters P_{ref} can depend on the configuration of the used PV-array.

f_{ref} [Hz] the nominal grid frequency, for example 50Hz.

R_{ref} [Ω] the resistance that let a current flow in the grid equal to I_{ref} .

G_{ref} [S] the conductance that let a current flow in the grid equal to I_{ref} .

X_{ref} [Ω] the reactance that let a current flow in the grid equal to I_{ref} .

L_{ref} [H] the inductance that let a current flow in the grid equal to I_{ref} .

C_{ref} [F] the capacitance that let a current flow in the grid equal to I_{ref} .

U_n [V]	the RMS value of the harmonic voltage (n^{th} harmonic).
I [A]	the RMS value of the current.
I_{n0} [A]	the RMS value of the harmonic current (n^{th} harmonic) at 0% THD on the voltage.
I_n [A]	the RMS value of the harmonic current (n^{th} harmonic).
P_n [W]	the delivered or dissipated active AC-power of the n^{th} harmonic.
φ_n [$^\circ$]	the phase angle between voltage and current of the n^{th} harmonic.
f_n [Hz]	the harmonic frequency.
n [1]	the harmonic number.
R_n [Ω]	the internal resistance of the DUT for the n^{th} harmonic.
G_n [S]	the internal conductance of the DUT for the n^{th} harmonic.
X_n [Ω]	the internal reactance of the DUT for the n^{th} harmonic.
L_n [H]	the internal inductance of the DUT for the n^{th} harmonic.
C_n [F]	the internal capacitance of the DUT for the n^{th} harmonic.

3.1.2 Formulas in practice

The quantities below are reference quantities and being used for normilization.

$I_{\text{ref}} = P_{\text{ref}} / U_{\text{ref}}$	I_{ref} gives always a positive result
$R_{\text{ref}} = (U_{\text{ref}})^2 / P_{\text{ref}} $	R_{ref} gives always a positive result
$G_{\text{ref}} = 1 / R_{\text{ref}}$	G_{ref} gives always a positive result
$X_{\text{ref}} = R_{\text{ref}}$	X_{ref} gives always a positive result
$L_{\text{ref}} = X_{\text{ref}} / (2 \cdot \pi \cdot f_{\text{ref}})$	L_{ref} gives always a positive result
$C_{\text{ref}} = 1 / (2 \cdot \pi \cdot f_{\text{ref}} \cdot X_{\text{ref}})$	C_{ref} gives always a positive result

The quantities below are calculated quantities and being used for calculation at a harmonic (n).

$f_n = n \cdot f_{\text{ref}}$	f_n gives always a positive result
$I_n = P_n / U_n$	I_n gives always a positive result
$R_n = (U_n)^2 / P_n$	a positive R_n means dissipation, negative means feed-back energy

$$G_n = 1 / R_n$$

a positive G_n means dissipation, negative means feed-back energy

$$X_n = (U_n)^2 / (P_n \cdot \tan \varphi_n)$$

a positive X_n means inductive, negative means capacitive

$$L_n = X_n / (2 \cdot \pi \cdot f_n)$$

L_n is always positive

$$C_n = 1 / (2 \cdot \pi \cdot f_n \cdot (-X_n))$$

C_n is always positive

Normalized formulas

$$I / I_{ref} = I_{n0} \cdot U_{ref} / |P_{ref}|$$

I / I_{ref} is always positive

$$G_n / G_{ref} = (U_{ref})^2 \cdot P_n / ((U_n)^2 \cdot |P_{ref}|)$$

a positive G_n / G_{ref} means dissipation, negative means feed-back energy

$$C_n / C_{ref} = (U_{ref})^2 \cdot (-P_n \cdot \tan \varphi_n) / ((U_n)^2 \cdot |P_{ref}| \cdot n)$$

a positive C_n / C_{ref} means capacitive, negative means inductive.

3.2 Test set-up

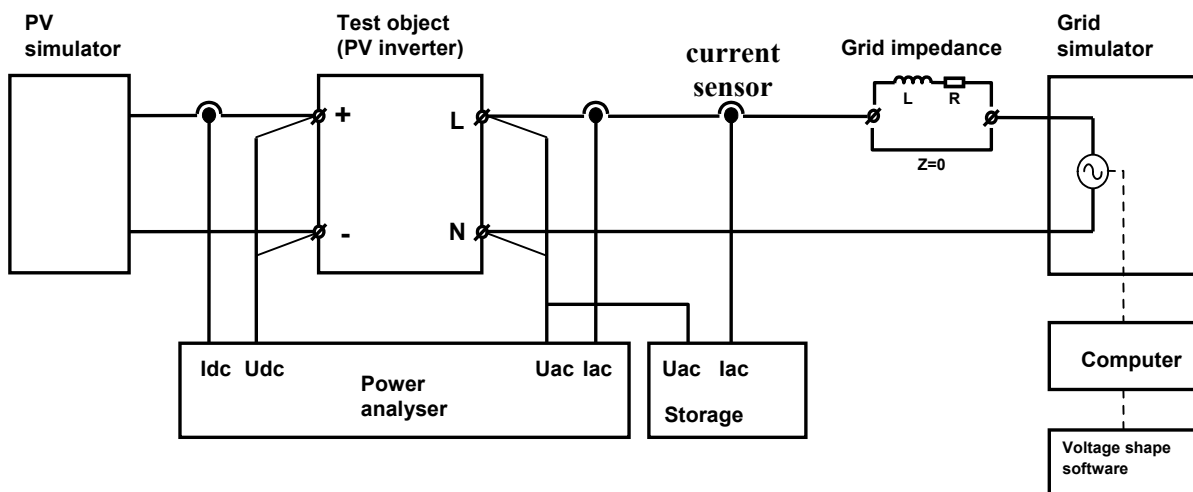


Figure 9 Test set-up

3.2.1 Measurement equipment

PV-simulator:

PV-simulator: DEPV0286

Grid-simulator:

Spitzenberger 4-quadrant amplifier, PAS 5000, ECN code: DEPV0138, DEPV0139 en DEPV0256

Personal Computer:

Tulip Vision Line Pentium II, met Windows 95, ECN code: P1483

Wave-shape software:
Power-analyser:
Storage-scoop:

Signal Manager 2.31 en Spitz & Spies
Norma, D6000, ECN code: DEPV0259
Tektronix, TDS3032, ECN code: DEPV0266.

3.3 Test objects

During this Complex Conductance Measurement the first 50 harmonics were examined on two single-phase small PV inverters with an output power of less then 300W and also on a passive load network for better understanding the results. Both inverters were equipped with fast switching power transistors en high frequency ferrite transformers.

In this project the inverters will be called: Inverter 1 and Inverter 2.

3.4 Test results

3.4.1 Test on a passive load network

Grid load: 53 Ω in parallel with 6 μ F
Grid impedance according to IEC 60725
 U_{ref} 230V
 I_{ref} 4.35A
 P_{ref} 1000W

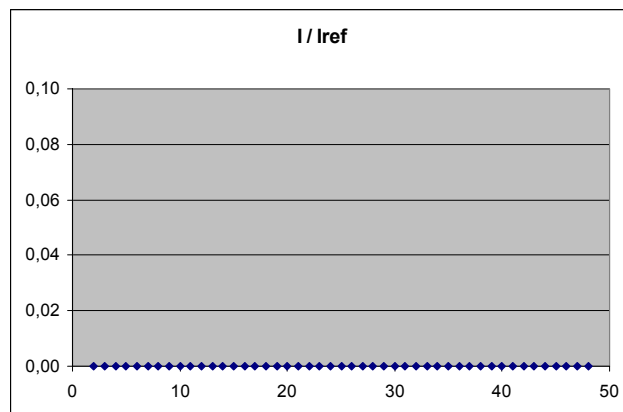


Figure 10 Normalized harmonic current emission of a R-C parallel network

As expected, in Figure 10 no harmonic current emission can be noticed from a passive network.

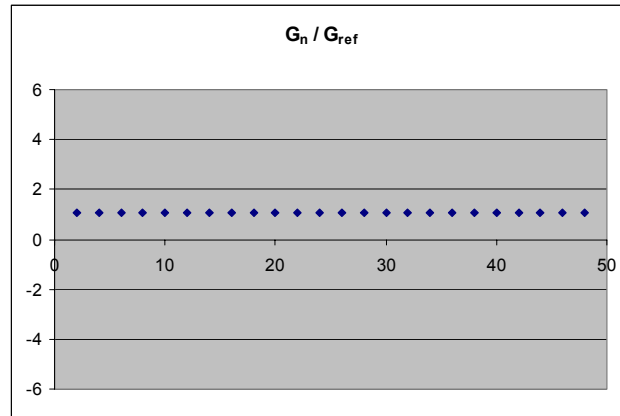


Figure 11 Normalized conductance of load network

The positive line in Figure 11 indicates that the conductance of the network remains dissipative over the frequency range.

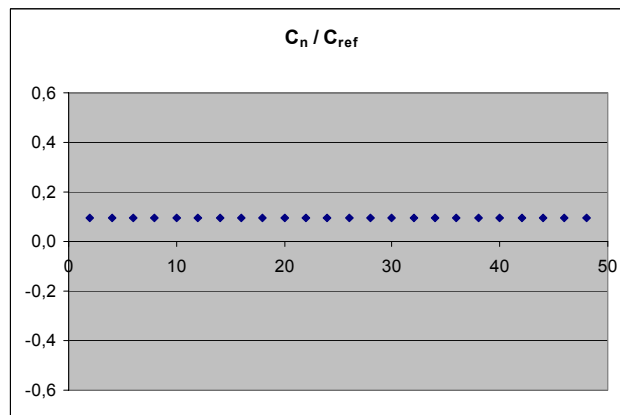


Figure 12 Normalized capacitance of load network

The positive line in Figure 12 indicates that the reactance of the network remains capacitive over the frequency range. The value of 0.1 could be expected because the capacitive current at the fundamental is 1/10 of the nominal current.

3.4.2 Test on inverter 1

Grid load:	Inverter 1
Grid impedance	according to IEC 60725
U_{ref}	230V
I_{ref}	0.87A
P_{ref}	-200W

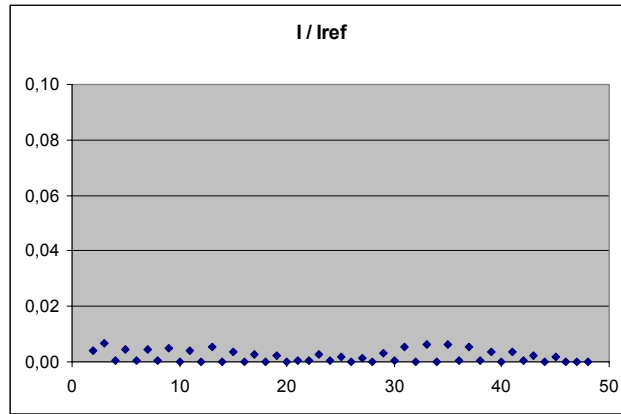


Figure 13 Normalized harmonic current emission of Inverter 1

In Figure 13 can be seen that the even harmonics are close to zero and the odd harmonics are present up to about 1 percent. For this reason excitation on the even harmonics is chosen during the measurements.

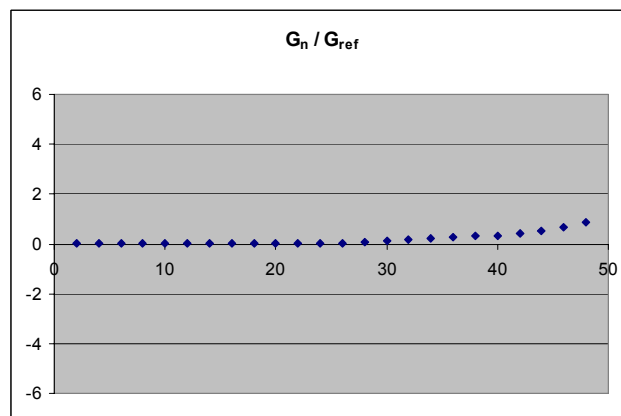


Figure 14 Normalized conductance of Inverter 1

In Figure 14 can be seen that G_n / G_{ref} is positive, this means that the inverter remains dissipative up to the 50th harmonic. G_n / G_{ref} is even close to zero up to the 30th harmonic, this means that the inverter practically does not respond on excitation with harmonic voltages.

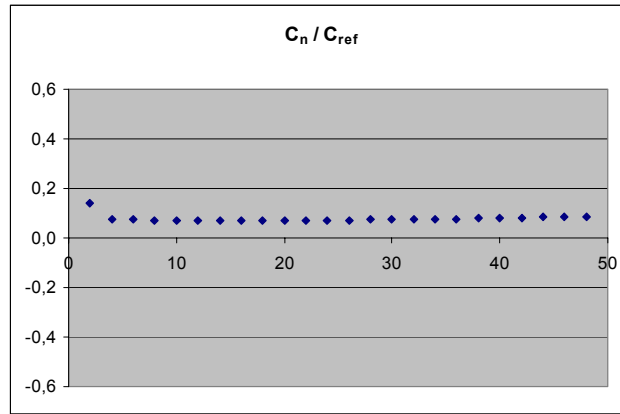


Figure 15 Normalized capacitance of Inverter 1

The line in Figure 15 remains practically flat over the 50 harmonics, so the output capacitance of the inverter remains constant in this range.

3.4.3 Test on inverter 2

Grid load:	Inverter 2
Grid impedance	according to IEC 60725
U_{ref}	230V
I_{ref}	0.43A
P_{ref}	-100W

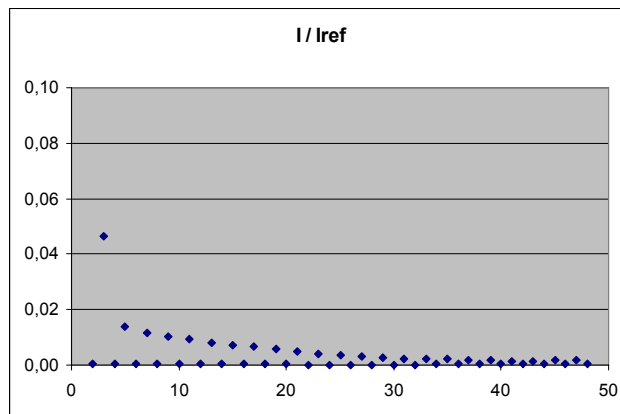


Figure 16 Normalized harmonic current emission of Inverter 2

In Figure 16 can be seen that the even harmonics are close to zero and the odd harmonics are present. For this reason excitation on the even harmonics is chosen during the measurements.

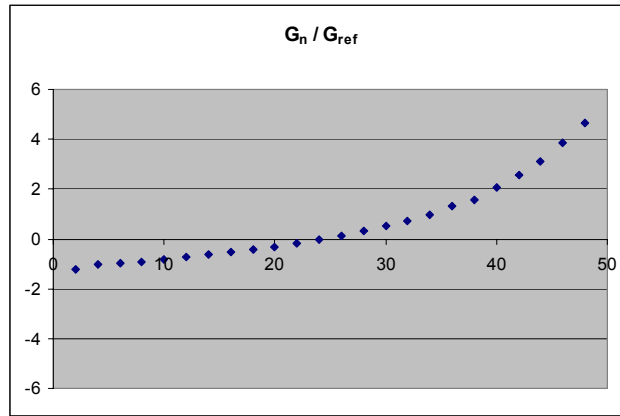


Figure 17 Normalized conductance of Inverter 2

In Figure 17 can be seen that G_n/G_{ref} is negative up to the 25th harmonic, this means that the inverter delivers power to the network and reduces the damping of oscillations in this frequency range, if present. G_n/G_{ref} is strongly positive from the 25th up to the 50th harmonic, this means that the inverter respond with harmonic currents during excitation with harmonic voltages.

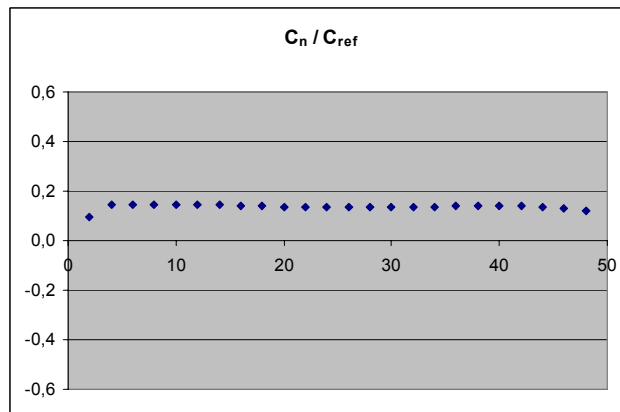


Figure 18 Normalized capacitance of Inverter 2

The line in Figure 18 remains practically flat over the 50 harmonics, so the output capacitance of the inverter remains constant in this range. The output capacitance here is higher than in Figure 15.

4 CONCLUSIONS AND REMARKS

4.1 Conclusions

The measuring method described in this report can be used to determine the frequency dependent parameters of inverters and loads. The results depend strongly on the inverter topology. Negative values for the normalized conductance appear to be possible for some types of inverters. As this may result in grid instabilities, inverters with negative conductance should only be used in projects with large-scale implementation of PV inverters when sufficient compensation is available.

Even with the simple model made, it is difficult to predict if amplification of the harmonic voltage at the PCC will occur. The chance on instability is even harder to predict due to the number of different parameters involved. Still some general conclusions can be made:

- $G_n / G_{ref} < 0$ will lead to a reduction of the damping of oscillations .
- A resonance frequency must be seen in relation with a possibility for excitation, therefore a higher resonance than the 40th harmonic is less harmful because of the lower background harmonic distortion in this range.
- A restriction on the values of G_n / G_{ref} (for example: only positive) is advisable.
- A review of the Standard 61000-3-2 on this matter is needed.
- Results of the mentioned Measurement Method can easily be used in a more complex simulation to predict the level of harmonic distortion and the possibility of resonance-effects.
- A further research on the behaviour of different kinds of loads in relation to harmonics is needed.

4.2 Remarks

The values measured for the conductance and the capacitance appear to be a continuous function of the frequency. There is no significant difference between even and odd harmonics.

Excitations with the harmonic voltages set on a phase angle of 0, 90 and 180 degrees have been done. This gave only a small deviation of the results for the higher harmonics. The influence of the phase angle on G_n / G_{ref} and C_n / C_{ref} is very small and therefore not presented.

The 61000-3-2 standard is nowadays used for testing and approving small inverters. This Standard limits the harmonic current injected (or absorbed) of the inverter as stated in Table 5. The main problem is that these limits are only required and tested with a pure sinusoidal voltage. In practice, as already stated there will always be some background harmonic voltage due to other load or other inverters.

Table 5 Limits according 61000-3-2

Harmonic order n	Maximum permissible harmonic current (A)
Odd harmonics	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
$15 \leq n \leq 39$	$0.15 \cdot (15/n)$
Even harmonics	
2	1.08
4	0.43
6	0.30
$8 \leq n \leq 40$	$0.23 \cdot (8/n)$

Fulfilling the requirements of this Standard does not guaranty the proper working in practice. A better way should be to measure I / I_{ref} , G_n / G_{ref} and C_n / C_{ref} and set some limits on these values. For the G_n / G_{ref} could be stated that a $G_n / G_{ref} > 0$ will not lead to a reduction of the damping of oscillations .

A small C_n / C_{ref} is advisable because possible parallel and series resonance's [3] will be higher in frequency; swelling due excitation in this area is rare, because of the lack of background harmonics.

5 REFERENCES

- [1] NTA 8494 (Netherlands Technical Agreement), a guideline for inverter testing.
- [2] NEC82 is the Netherlands National Committee for Solar energy systems of the: International Electro technical Commission (IEC) and the European Committee for Electro technical Standardization (CENELEC).
- [3] J.H.R. Enslin; W.T.J. Hulshorst; J.F. Groeman; A.M.S. Atmadji; P.J.M. Heskes; A. Kotsopoulos: "Harmonic Interaction between Large Numbers of Photovoltaic Inverters and the Distribution Network". KEMA-ECN Report: 40210004 TDC 02-29719A (confidential).
- [4] P.J.M. Heskes, P.M. Rooij, H.E. Oldenkamp: "Photovoltaische Inverters and their Behaviour on Poor Power Quality of the Distribution Network " in Dutch: "Photovoltaische Inverters en hun gedrag op matige netkwaliteit". ECN report: ECN-C--03-105.
- [5] KEMA report: "Power Quality Monitoring 2002" in Dutch: "Spanningskwaliteit in Nederland" (confidential).
- [6] EN 50160, voltage characteristics of the electricity supplied by public distribution systems.