PREDICT THE LEVEL OF HARMONIC DISTORTION DUE TO DISPERSED GENERATION

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INTRODUCTION

A simple though accurate method is developed to estimate the pollution of the electricity network with harmonics in case a large number of inverters is presented. The method is called the 'Complex Conductance Measurement Method'. Although this method is written for inverters of small grid connected micro generators, it can also be applied for all kinds of loads. A measuring method to determine the necessary frequency dependent parameters of inverters and loads in general is presented.

1. THE SIMPLE MODEL

The simplest model of a grid connected PV-system consists of a grid connected to a single load and a single inverter as shown in figure 1[1],[2].

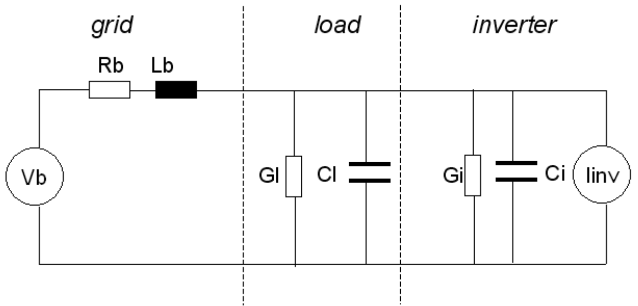

Figure 1: Simple model for harmonic calculations

The grid consists of:

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

The load is modelled as a conductance Y=Gl+jωCl. Both Gl and Cl may vary with the frequency. The inverter is modelled with:

- A harmonic current source, modelling the harmonic currents of the inverter when there is no background voltage distortion
- The capacitor of the inverter which can be calculated by measuring the imaginary part of the power on the connection point of the inverter, Ci
- The conductance of the inverter which can be calculated by measuring the real part of the power on the connection point of the inverter, Gi

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

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

V_b	= the grid background harmonic voltage distortion
V	= the harmonic voltage at the PCC (connection point load and inverter)
R_b	= the grid resistance
L_b	= the grid inductance
I_{inv}	= the harmonic current injected by the inverter
C	= the total capacitor (sum of load and inverter capacity)
G	= the total conductance (sum of load and inverter conductance)

This system will become unstable when the denominator of the transfer function becomes near zero. This occurs when:

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

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 occurs, as at the resonance frequency the dissipation in the series resistor R_b equals the power delivered by the negative conductor G. Total instability can only occur for negative values of G. However, for low values of the denominator, significant amplification of harmonic voltages may occur.

2. MODELLING THE GRID

Constructing a model for the grid, the most important parts are the model for the MV/LV-transformer and the LV-cable. The transformer can be modeled as a constant resistance and an inductance. A cable cannot so easily be modeled as a constant resistance and inductance. Due to the skin- and proximity effects the resistance of the cable will be influenced by the frequency [3]. Figure 2 shows the resistance of a 240 aluminum MV-cable in the frequency domain.

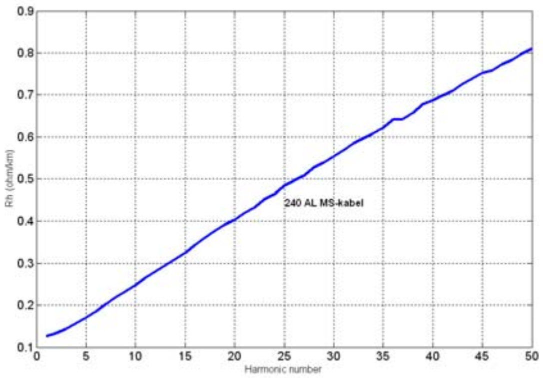

Figure 2: Resistance 240 Al MV-cable

The LV-cables will have a similar behavior, although the increase will be less, using cables with a smaller cross sectional area.

3. MODELLING THE INVERTER

The inverter parameters can be measured by means of a harmonic power analyser and two AC-power sources in series. The test set-up is shown in figure 3. The electrical circuit is shown in figure 4.

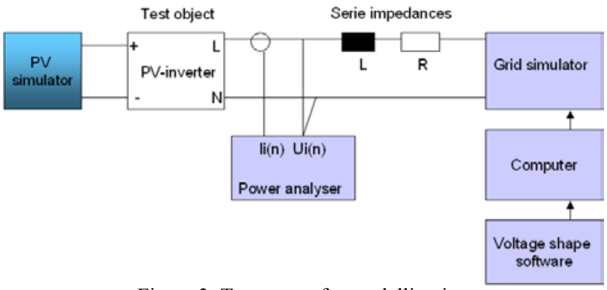

Figure 3: Test set-up for modelling inverter

The inverter to model is the test object and is connected on the DC-side to a PV-simulator. On the AC-side the inverter is via a grid impedance connected to a grid simulator. The grid simulator is an AC-source, capable to produce the fundamental voltage and one or more harmonic voltages.

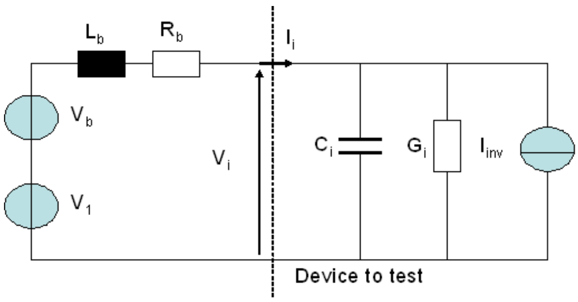

Figure 4: Electrical circuit for harmonic analyse

With this grid simulator, voltage source V_1 is created on the nominal grid voltage and frequency to bias the inverter in its proper working area. The second voltage source is created for introducing harmonic voltages. 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 U_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 value of L_b and R_b should be kept as low as possible.

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 0.2% 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 conductance and capacitance of the injected harmonic can be calculated with:

$$G_i = \frac{P_i}{V_b^{\,2}} \quad \text{and} \quad C_i = \frac{Q_i}{V_b^{\,2}}$$

- The measurement of step 2 is repeated for all harmonics of which the injected harmonics under step 1 was smaller than 0.2% of the fundamental current.

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.

$$\text{This gives:} \quad G_{ref} = \frac{P_{nom}}{V_{nom}^{\,2}}$$

Note that this equation should only be used for the fundamental frequency. The normalized inverter conductance for the i^{th} harmonic can be calculated with:

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

Similar to above it is also more practical to use a normalized value of the capacitance. Therefore C_i will by 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.

$$\text{This gives:} \quad C_{ref} = \frac{P_{nom}}{\omega_i \cdot V_{nom}^{\,2}}$$

Note that this equation again should only be used for the fundamental frequency.

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

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

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

On a 50Hz/230V grid:

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

$$\text{and } \frac{G_{ref}}{P} = \frac{1}{V_{nom}^{\ 2}} = 18.9\frac{\mu S}{W}$$

For several inverters this procedure has been followed. The results of the measurement are shown in figure 5 (I_{inv}, shown as Ih/In), 6 (G/G_{ref})and 7 (C/C_{ref}) for a single inverter.

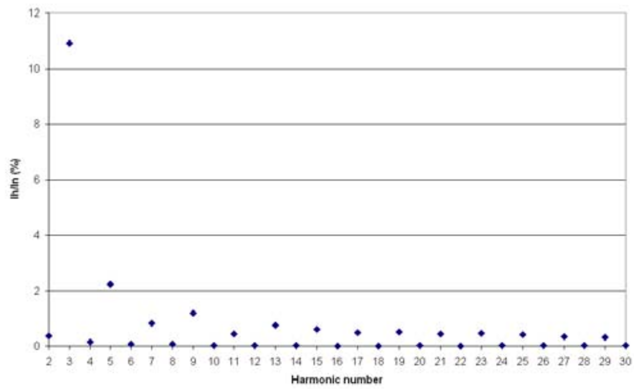

Figure 5: Harmonic currents inverter (Vb=0)

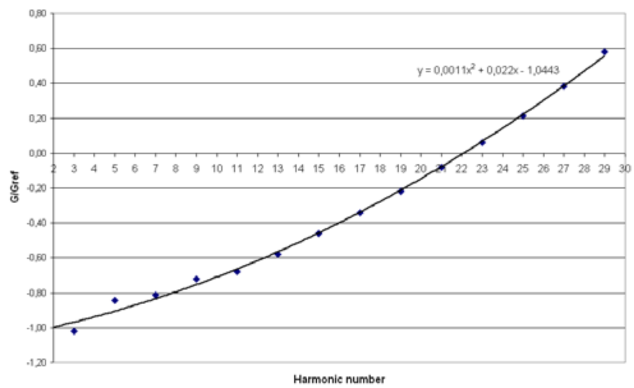

Figure 6: G/Gref for measured inverter

In figure 6 a trend line is included with the formulae which can be used for calculations.

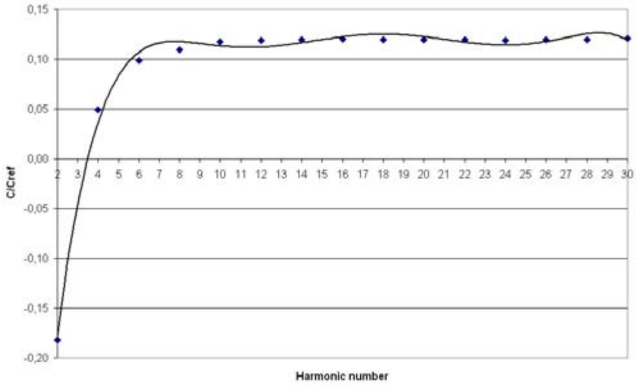

Figure 7: C/Cref for measured inverter

4. MODELLING THE LOAD

The load can be modeled with the same measuring method as described for the inverters. Of course, there are many kinds of loads with their specific parameters. In this area still a lot of work has to be done. As example the results of these measurements on a specific Personal Computer are shown in figures 8, 9 and 10.

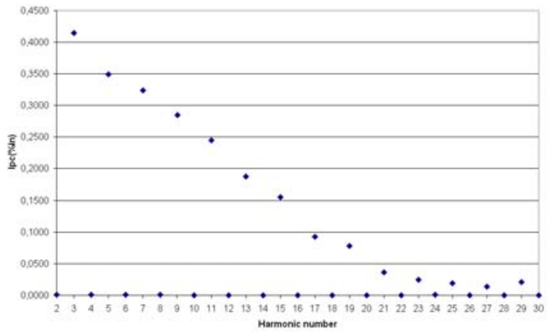

Figure 8: Harmonic current personal computer (Vb=0)

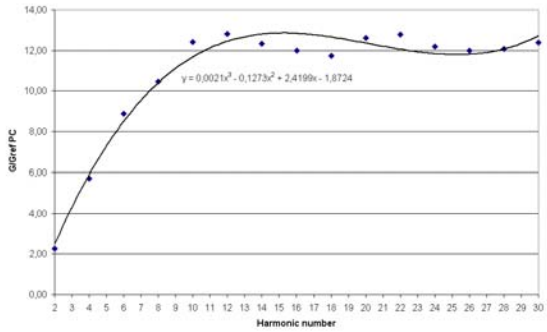

Figure 9: G/Gref personal computer

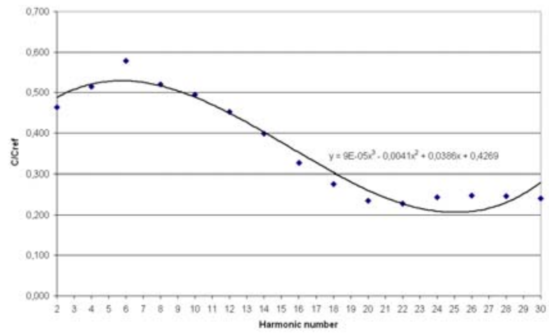

Figure 10: C/Cref personal computer

These figures show that the harmonic behavior of this load for each separate harmonic is different. This is the case with most kind of loads, which makes calculations in this field very difficult.
Still, the method can be used for several applications. The parameters can be used to characterize the equipment, set limits for a standard, test the equipment according this Standard and predict a possible harmonic problem in practice.

5. PRACTICAL USE

The proposed method of characterizing inverters and loads can be used in Standards for harmonic distortion. Today the standard used for inverters is IEC 61000-3-2 [4]. This Standard and the class A, where mostly is referred to, only limit the harmonic current in an absolute way. There is no relation with the nominal power of the inverter and the influence of harmonic background distortion is not considered.

One important issue to avoid harmonic distortion is to pay attention to negative conductance. Negative values for the normalized conductance appear to be possible for several types of inverters. As this may result in considerable harmonic voltage pollution of the grid, inverters with negative conductance should only be used in projects with large-scale implementation of PV inverters, when sufficient compensation is available. Another important issue to avoid harmonic distortion is to pay attention to high values of capacitance. High values for the normalized capacitance appear to be possible for some types of inverters. These aspects are important and not yet considered in the Standard.

As described before the method can be used to predict possible harmonic problems. As example of a harmonic resonance problem, figure 11 shows an extreme harmonic distortion on the 15th harmonics. This distortion was observed in a situation where a lot of the inverters, characterized by the figures 5, 6 and 7 where used.

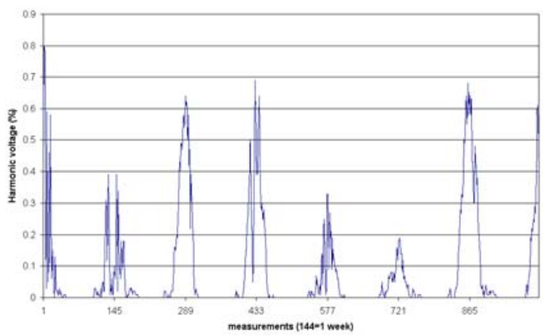

Figure 11: Measured 15th harmonic voltage

Using the grid parameters in the given situation, the inverter parameters and neglecting the load the harmonic voltage on the measured pcc could be calculated using formulae (1).
The results are shown in figure 12, with a background voltage of all the harmonics set on 1 V. Figure 12 indeed predict that the 15th harmonic voltage will be multiplied with a factor 8, assuming that the starting background voltage is 1V.

More precise results can be found when the background voltage can be measured before connecting all the PV-systems.

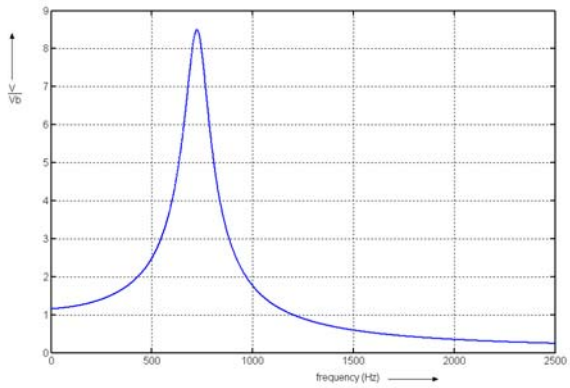

Figure 12: Calculated harmonic voltages

6. CONCLUSIONS

Using the described measuring method can lead to an useful characterizing of inverters and all kind of loads in relation with their harmonic behavior. These parameters Ih/In, G and C can be used in Standards in a way that the reaction on background harmonic voltages can be described and limited.
Knowing these parameters of all the equipment placed in the network and of the network itself makes it possible to calculate harmonic currents and voltages on every point in the network.
Rough calculation already shows that a negative conductance can lead to a significant increase of harmonic distortion and should be avoid for this reason. Furthermore the capacity of equipment should be limited.
A further research on the G- and C-values of all kinds of loads is advisable for achieving more precise results.
Characterizing a total network with all the loads connected is useful future work.

7. REFERENCES

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