

ADDITIONAL REQUIREMENTS FOR PV INVERTERS NECESSARY TO MAINTAIN UTILITY GRID QUALITY IN CASE OF HIGH PENETRATION OF PV GENERATORS

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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. Whether or not these phenomena will occur depend on the high frequency parameters of the inverter(s), the load and the utility grid. This paper describes a way to model the harmonics behaviour in a utility grid. Next a simple test method is presented that can be used to measure the high frequency parameters of the loads and the inverters accurately.

Keywords: Inverters, Modelling, Grid-Connected

1 INTRODUCTION

With the steady growth of PV installations, the penetration of PV-generators in the built environment will grow as well, leading 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 the inverters and the loads.

2 BASIC OF THE HARMONICS' MODEL

2.1 Conversion to dimensionless quantities

In this article most values are converted to dimensionless quantities by dividing them by a reference quantity; all quantities written with 'lower case italics' are dimensionless. The reference voltage is always the nominal grid voltage, the reference frequency is always the fundamental frequency of the grid and the reference power is the nominal power. If the nominal power is not specified then the nominal apparent power is used as reference power.

For a given grid voltage and frequency the following reference quantities can be calculated:

- apparent power: $S_{nom} = I_{rated} \cdot V_{nom}$
- resistance: $R_{ref} = \frac{V_{nom}^2}{P_{nom}}$ or: $R_{ref} = \frac{V_{nom}}{I_{rated}}$
- conductance: $G_{ref} = \frac{1}{R_{ref}}$
- inductance: $L_{ref} = \frac{R_{ref}}{2\pi f_{grid}}$
- capacitance: $C_{ref} = \frac{G_{ref}}{2\pi f_{grid}}$

2.2 Modelling the grid

In this model the high voltage distribution network is not taken into account. It is assumed the grid consists of an ideal voltage source followed by a utility transformer

and the low voltage cable network. A utility transformer is usually characterized by the following quantities:

- The nominal apparent power, usually given in kVA.
- The nominal output voltage.
- The relative short circuit voltage u_{short} , usually in the range from 4% to 6%.
- The copper (conduction) losses at nominal current, usually given in Watts. Similar to the relative short circuit voltage it is also possible to define the relative short circuit losses as:

$$p_{short} = \frac{P_{cu}}{P_{nom}}, \text{ usually } p_{short} \text{ is in the order of } 1\%.$$

In practice the output capacity of the transformer and the cables are very small compared to the capacities of the load (see later). Therefore, for the frequency range of interest, let's say the first 100 harmonics, the transformer can be modelled accurately by a voltage source with a series inductor and a series resistor. The series inductor is caused by the transformer leakage inductance. The series resistor is caused by the resistance of the windings.

Using the dimensionless definitions (par. 2.1) the transformer relative series resistance will be equal to the relative short circuit voltage of the transformer:

$r_s = p_{short}$, as mentioned before, r_s is in the order of 1%. Due to the skin effect and proximity effects in the windings r_s will increase for higher harmonics.

The short circuit voltage of a transformer consists of the sum of the voltages of the series inductor and the series resistor. As these voltages have a phase difference of 90 degrees, the relative series inductance becomes:

$l_s = \sqrt{u_{short}^2 - p_{short}^2}$, usually l_s will be in the order of 4% to 6%.

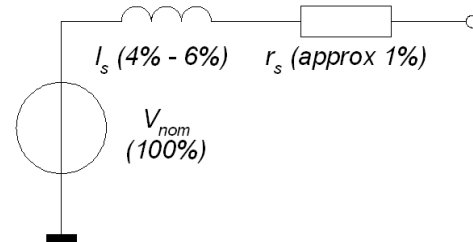


Figure 1: Utility transformer model.

2.3 Modelling the cables

The properties of the low voltage distribution cables are characterized by three quantities: the series resistance, the series inductance and the parallel capacity.

The series resistance of low voltage distribution cables decreases linear with the conductor cross section. However, the current rating of these cables is roughly proportional to the square root of the conductor cross section.

The series inductance of these cables is hardly affected by the cross section of the conductors. Cables with a conductor cross section varying from 10 mm² to 240 mm² have a series inductance in the range of 0.15 mH/km to 0.3 mH/km.

The parallel capacity of low voltage distribution cables is hardly affected by the cross section of the conductors. Shielded cables with a conductor cross section varying from 10 mm² to 240 mm² have a capacity in the range from 100 nF/km to 220 nF/km.

In table 1 an overview of the electrical properties of a shielded power distribution cable is given. The values apply for one conductor in a cable with 4 conductors. A shielded cable is chosen as a worst case: it has the highest capacity. In table 2 the electrical properties are converted to relative, dimensionless quantities, assuming the cables are used at 230 Volt and 50 Hz. The power through each cable at rated current is used as the reference power of each cable.

Table 1: Overview of the electrical properties of a shielded power distribution cable

Conductor cross section [mm ²]	Rated current [A]	Series resistance [Ohm/km]	Series inductance [mH/km]	Parallel capacity [nF/km]	P @ 230 V [kW]
10	61	2.330	0.28	114	14.0
16	79	1.470	0.27	120	18.2
25	101	0.927	0.26	130	23.2
35	122	0.669	0.23	137	28.1
50	144	0.494	0.23	147	33.1
70	178	0.344	0.20	163	40.9
95	211	0.248	0.19	176	48.5
120	240	0.198	0.18	187	55.2
150	271	0.161	0.17	197	62.3
185	304	0.131	0.17	205	69.9
240	351	0.102	0.17	217	80.7

In practice the length of each cable is limited by the minimum voltage at the end of the cable at maximum load. The voltage drop at the end of the cable consists of the vector sum of the voltage drop in the transformer and the cable. Assuming that the cable is connected to a transformer with a relative series inductance of 4% and a relative series resistance of 1% the cable length for a voltage drop of 10% can be calculated. The table shows this length and also the relative series resistance, inductance and capacitance for this length.

From the tables it can be concluded:

- The maximum relative parallel capacitance is in the order of 0.002% to 0.004%. As will be shown later, this is very small compared to the capacity of the loads and the inverters, and therefore can be ignored in the model.
- When the cable network consists of a lot of thin (10 mm²) distribution cables in parallel the impedance of the cable network can be modelled as a relative series resistor of 8% in series with a relative series inductor of 0.3%. So in that case the cable is mainly resistive.
- When the cable network consists of a few thick (240 mm²) distribution cables in parallel the impedance of the cable network can be modelled as a relative series resistor of 1.9% in series with a relative series inductor of 5.6%. So in that case the cable is mainly inductive.

- So, in practice, for a good designed network, the range of possible values for the relative series resistance and relative series inductance is limited to the values given in table 2.

Cond cross section [mm ²]	Dimensionless at 230V/50Hz			Max cable length for 90% V at end [km]	Dimensionless at max cable length		
	series res [%/km]	series ind [%/km]	series cap [%/km]		series res [%]	series ind [%]	series cap [%]
10	61.8	2.3	0.014	0.162	10.0	0.4	0.002
16	39.0	2.9	0.011	0.256	10.0	0.7	0.003
25	24.6	3.6	0.009	0.405	9.9	1.5	0.004
35	17.7	3.8	0.008	0.560	9.9	2.1	0.005
50	13.1	4.5	0.007	0.751	9.8	3.4	0.006
70	9.1	4.9	0.007	1.061	9.7	5.2	0.007
95	6.6	5.5	0.006	1.436	9.4	7.9	0.009
120	5.3	5.9	0.006	1.739	9.1	10.3	0.010
150	4.3	6.3	0.005	2.061	8.8	13.0	0.011
185	3.5	7.1	0.005	2.355	8.2	16.6	0.011
240	2.7	8.2	0.004	2.639	7.1	21.5	0.012

Table 2: Some dimensionless quantities of one conductor of a typical shielded power distribution cable.

Finally it can be concluded that using only the impedance of the utility transformer represents the strongest possible grid. It is important to realize that, especially for harmonics, there is no such thing as a "strong grid".

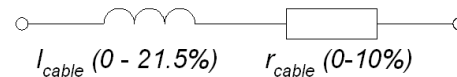


Figure 2: Cables' model

2.4 Modelling the loads

In a utility grid, many types of dissipative loads are used. Basically all these loads can be seen as "a complex impedance". However, except for some purely resistive or capacitive loads, all practical loads will generate harmonic currents. Therefore, a load must be modelled as "a complex impedance" together with an (harmonic) current source.

For higher harmonics many loads become capacitive. Since all the loads are connected in parallel the best way for modelling the loads is to use parallel elements. Thus the load will be modelled as the parallel connection of a conductor, a capacitor and a current source. The value of each element is usually a function of the harmonic's number. Note: using a capacitor is not a limitation for the model. For any frequency an inductor can be seen as a negative capacitor of which the capacity is a function of the frequency.

The model for the load is shown in figure 3. Note that the values for the conductance and the capacitance can be well above 100%. This will be discussed in section 3.

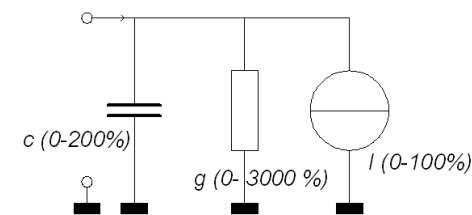


Figure 3: Loads' model

2.5 Modelling the inverters

The inverters can be modelled in exactly the same way as the loads: the parallel connection of a capacitor, a conductor and a current source. Again, each element is a function of the frequency.

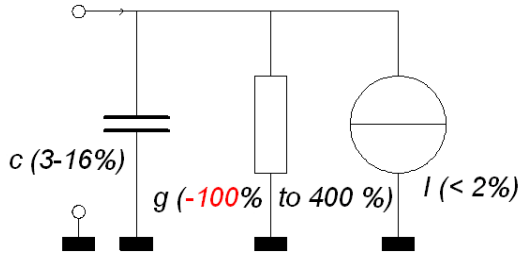


Figure 4: Inverters' model

It is important to realize that besides the current source also the conductor can be a power source for certain frequencies. In that case the conductance will be negative at these frequencies. Laboratory measurements have shown this occurs for some types of inverters. In Figure 4 the inverter model and the range of values that were measured are given. The values will be discussed in section 3.

3 MEASURING THE INVERTER AND LOAD PARAMETERS

3.1 Inverter test setup

In general the values for the inverter and the load parameters i , g and c depend on the harmonic's number.

Frequency dependent parameters are measured as follows:

1. First the devices under test are properly dc-biased.
2. Then a small ac signal is super imposed on the bias level
3. Next, the impedance can be determined by measuring the input signal voltage and the input current.

For ac-loads and inverters the same procedure can be used. However, the devices must be ac-biased instead of dc-biased [Figure 5].

The series impedance in figure 5 represents the total output impedance of both voltage sources. In practice, the easiest way to measure the input current and the input voltage and their phase is by means of a harmonics analyzer. The limitation of this procedure is that the parameters can only be measured exactly at the selected harmonics number. In practice this is, however, rather acceptable. A requirement for using the harmonics analyzer is that the superimposed frequency is synchronized with the fundamental.

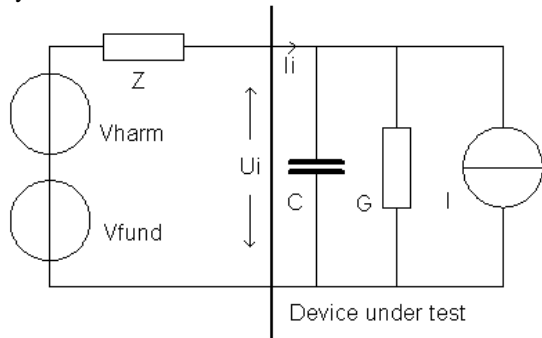


Figure 5: Inverter test setup

3.2 Measuring the harmonics' parameters

Measurement of each harmonic parameter was executed as follows:

- Step 1: First the output of the harmonic generator is set to zero.
- Step 2: Then the input voltage, current, apparent power, power and reactive power of the harmonic are determined and then the relative dimensionless quantities $v_{n,bias}$, $i_{n,bias}$, $s_{n,bias}$, $p_{n,bias}$ and $q_{n,bias}$ can be calculated. It is also possible to measure voltage, current and phase angle. However, it seems that harmonic power analyzers perform more accurate when voltage and power are measured.
- Step 3: Next the output of the harmonic generator is set to, for example, 1% of the nominal grid voltage.
- Step 4: The input voltage, current, apparent power, power and reactive of the harmonic are measured again and then the corresponding relative dimensionless quantities can be calculated again. This gives: $v_{n,bias+ext}$, $i_{n,bias+ext}$, $p_{n,bias+ext}$, $s_{n,bias+ext}$ and $q_{n,bias+ext}$.
- Step 5: Finally the relative harmonic current, the relative harmonic conductance and the relative harmonic capacitance can be calculated by:

$$g_n = \frac{p_{n,bias+ext} - p_{n,bias}}{(u_{n,bias+ext} - u_{n,bias})^2}$$

$$c_n = \frac{q_{n,bias+ext} - q_{n,bias}}{n(u_{n,bias+ext} - u_{n,bias})^2} \text{ and}$$

$$i = i_{n,bias} \sqrt{\left(\frac{p_{n,bias} - g_n u_{n,bias}}{s_{n,bias}} \right)^2 + \left(\frac{q_{n,bias} - n c_n u_{n,bias}}{s_{n,bias}} \right)^2}$$

Remarks:

1. In case the voltage of the harmonic which is measured in step 2 is zero or very small, let's say more than 10 times smaller than the injected voltage, the equations given in 5 can be simplified into:

$$g_n = \frac{p_{n,bias+ext}}{u_{n,bias+ext}^2}, c_n = \frac{q_{n,bias+ext}}{n u_{n,bias+ext}^2} \text{ and } i = i_{n,bias}$$

- 2: For an acceptable accuracy the harmonics in the bias voltage should be as low as possible.
- 3: The accuracy becomes poor when the harmonic of the current which is measured in step 2 is much larger than the harmonic current which is injected during step 4. Since generally the even harmonics will be much lower than the odd harmonics the accuracy of the conductance and capacitance measurements of the even harmonics are more reliable. In fact, to save time, it can be considered to skip step 5 for the odd harmonics for determining the conductance and capacitance. In that case the requirement of remark 1 must be met and the simplified equations as given in remark 1 should be used.
- 4: The phase of the injected harmonic does not affect the measurement.
- 5: For most inverters good results were obtained for harmonic injected voltages of 3% for low harmonics and 1% for the higher harmonics. For loads with high harmonic emission like rectifiers the injected voltages should be kept as low as possible. Here levels in the order of 0.5% to 1% have been used to obtain good results.

3.3 Test results

In total six inverters were tested according to the described test method. In this paper only the results of two inverters are presented [Figures 6-7]. The complete data of the inverters can be downloaded from our website www.oke-services.nl.

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. The shape of the conductance and the capacitance curves depends strongly on the inverter topology.

It appears that for inverter 4 the conductance and the capacitance are more or less independent from the inverter power, whereas for inverter 6 these parameters are clearly a function of the inverter power. Also it can be seen that the conductance of inverter 6 is negative for the first 25 harmonics.

Figure 8 shows the conductance of a 120 Watts switched mode power supply loaded for 78%. Surprisingly the normalized conductance increases until approximately 27 for higher harmonics.

4 CONCLUSIONS

The measuring method described in section 3 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 not be used in large scale projects.

The project will be continued, and we hope to present you a system model at the next conference.

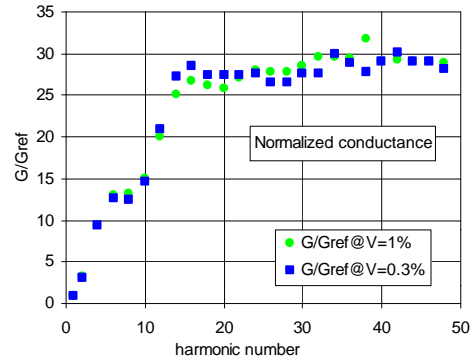


Figure 8: Normalized conductance of 120 W supply, loaded at 78%.

5 REFERENCES AND ACKNOWLEDGEMENTS

5.1 References

[1] Oldenkamp, H, Modelling harmonics in grid-connected PV-systems, June 2004

5.2 Information

For more information visit www.oke-services.nl, offering the possibility to download the full report “Modelling harmonics in grid-connected PV-systems”.

5.3 Acknowledgements

The authors would like to thank SenterNovem for their financial support to the “development of a decent inverter”.

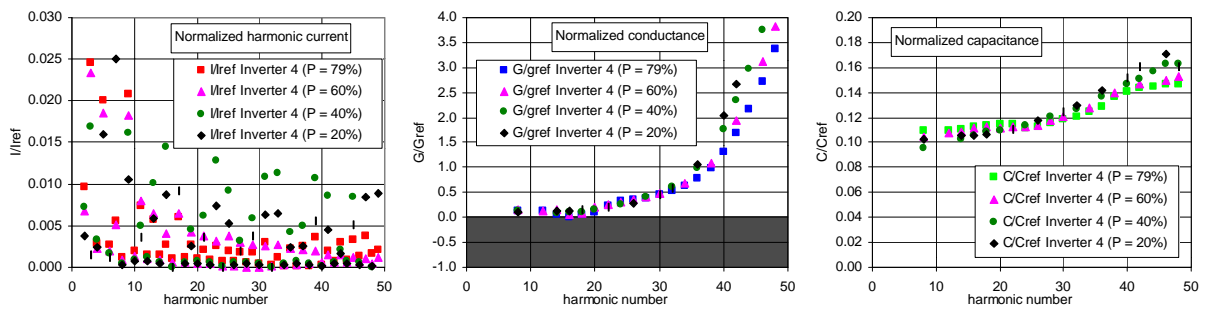


Figure 6: Test results inverter 4: normalized harmonic current, conductance and capacitance

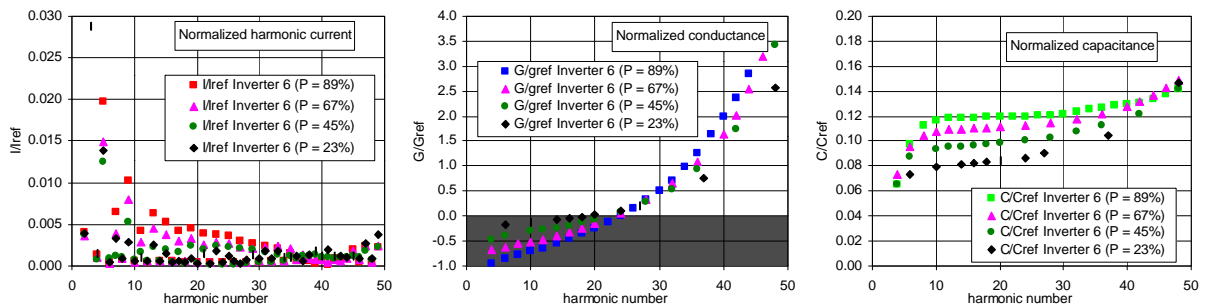


Figure 7: Test results inverter 6: normalized harmonic current, conductance and capacitance