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POWER QUALITY BEHAVIOUR OF DIFFERENT PHOTOVOLTAIC INVERTER TOPOLOGIES

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Abstract – In this paper several inverter topology concepts from the group of small, single-phase, self-commutated PV inverters will be discussed. Current-feedback loop and different kinds of reference sources of these PV inverters will also be discussed. Active and passive reductions of harmonic current emission are investigated. Laboratory measurements on the harmonic interaction between the inverter and a model of the public electricity network were made on a number of commercially available inverters. In this paper results of one single inverter are presented.

This paper should be seen as a gentle warning for particular inverter interaction problems.

1. RENEWABLE DRIVE IN THE NETHERLANDS

The Dutch Government and utilities have promoted the use of renewable energy (Green Energy) with subsidies and implementation programs. They also introduced green labels. Some examples include “Green” suburbs where Roof-mounted PV arrays are installed on most of the roofs of individual homes and communal buildings.

2. POWER QUALITY PROBLEMS WITH PV INVERTERS

Large numbers of PV inverters on low-voltage feeders can give power quality problems and may result that in certain cases, temporarily the national standard for power quality EN50160 [1] is exceeded. This is the result even when all the PV inverters individually satisfy the IEC 61000-3-2 [2] specification.

Not completely covered by standards at this moment is the effect of harmonic current emission by PV-inverters as a response on harmonic distortion of the grid voltage. Also not completely covered by standards at this moment is the production of harmonic current emission due to a resonance phenomenon between the network and PV inverters.

All these effects can lead to a higher harmonic current emission of the PV-inverters, which is design dependent. These harmonic emissions can be minimised by good design practice, which anticipates on future standardisation.

3. POWER QUALITY OF PV INVERTERS, RELATED TO TOPOLOGY AND CONTROL ASPECTS

Converters for PV systems can be divided into two groups, namely: Line commutated inverters and self commutated inverters. Line commutated inverters are commonly used for high power converters, while self-commutated converters are commonly used for small PV-inverters. Only inverters with line currents up to maximum 16 amperes per phase and therefore only self-commutated inverters will be discussed. A further limitation will be the focus on single-phase inverters.

Within the mentioned limitations, PV inverters consist in general of different stages and transformer options. To comply with standards, these inverters with their pulse-width-modulation (PWM) converter controllers generate a sinusoidal output current. In practice switching frequencies of 20 - 500 kHz are used in different power stages.

Several inverter concepts are used in these group of small single-phase inverters, examples are:

- single-stage concept of H-bridge pulse-width-modulated (PWM) DC-DC converter directly coupled to the grid
- single-stage concept of H-bridge PWM DC-DC converter coupled to the grid with a low frequency (LF) isolation transformer, see Fig.1
- multi-stage concept of PWM DC-DC converter front-end, with 50Hz unfolding bridge directly coupled to the grid, see Fig. 2

- multi-stage concept of PWM DC-DC converter front-end with 50Hz unfolding bridge coupled to the grid with a LF-isolation transformer
- multi-stage concept of PWM DC-DC converter front-end including a high-frequency (HF) isolation transformer, and a 50Hz unfolding bridge coupled to the grid.

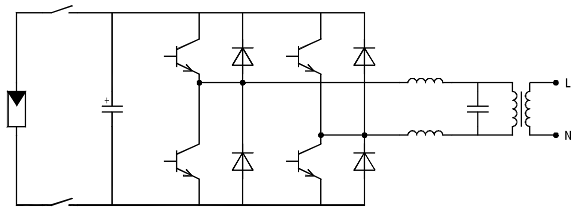

Fig. 1: Single-stage H-Bridge PWM converter and low-frequency transformer

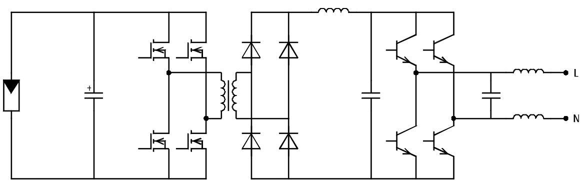

Fig. 2: Multi-stage high-frequency transformer H-Bridge PWM Converter with low-frequency unfolding bridge

Inverters can make use of an extra input buck or boost converter to gain the dynamic range at the input. In these topologies the energy storage capacitor, needed in one-phase inverters, can be placed at the input of the inverter or between the two converter stages. These types cover the majority of small single-phase inverters.

For all these inverter types the AC output current will mainly be characterised by the current-feedback control loop. The majority of these inverters are capable of self-generating a 50Hz sinusoidal output current based on internal processor tables and synchronisation with the supply voltage. This synchronisation is often done by means of a Phase-locked Loop (PLL).

Some inverters combine the reference source and the synchronisation in the grid voltage, by using the shape of the grid voltage as a reference source. However if the grid voltage is polluted, the reference source will also be polluted and the current control loop of the inverter pollutes his output current accordingly. Filtering out the pollution using such a controller is difficult to do, while obtaining a good (unity) power factor.

If it is desired to design an inverter with an unpolluted sinusoidal output current shape, even if the grid voltage is polluted with harmonics, using a good reference source is the first demand. Further the inverters output impedance, as function of the frequency has to be high as well. In practice the output impedance has to be high up to the 40th harmonic, to avoid harmonic current pollution as an interaction on harmonic voltage pollution.

High output impedance can be achieved actively by means of the current control loop performance, but also in a passive way. The passive way can be achieved by inductance in the inverters output circuit, i.e. the leakage inductance of the LF transformer. In practice this is only useful for the higher harmonics. Active compensation remains necessary for a good overall result. For modern high frequency switching inverters, adding inductance for reducing the lower harmonics is very bulky and costly.

To improve the current source character, a controller with a sufficiently high gain-bandwidth product of the current feedback loop is the first demand. For a good result the place of the current sensor in the inverter circuit is important. The best place to sense the output current is directly on the output terminals of the inverter, however in general EMI filters and output filter capacitors are the last components in the output circuit. Very often these current sensors will be combined with current sensors already needed in a DC-DC converter stage. Al these aspects makes that the current source behaviour of the inverter is commonly not as good as it can be.

Inverters with their fast switching power electronic components inside, are potential EMI sources. For this reason high frequency (HF) filtering in an inverter is needed. A low frequency filter is used to filter out distortion from the switching frequency, which lies generally below the EMI filtering range. The filter components in these types of filters are inductors and capacitors located at the input and output side of the inverter.

The output capacitor(s) of the inverter strongly reduce the current source behaviour of the inverter and can also be mainly responsible for setting up a resonance circuit together with the network reactance (transformer and cable reactance). These effects are not detected or reduced by the current control loop of the inverter, if the current loop of the inverter is not optimised for this. At this moment such an optimisation is not driven by obliged standards.

For grid-connected inverters with output current distortion as an interaction with the grid voltage distortion, this interaction character will be gained by the following items:

- current-shape reference source is a copy from the grid voltage
- output impedance as a function of the frequency is poor
- high output capacitance.

For improvement of this character the following may be done:

- current-shape reference source be generated from a sinusoidal table in the processor
- output impedance as a function of the frequency should be high
- a low output capacitance should be used as filter.

4. EXPERIMENTAL HARMONIC DISTORTION VALIDATION

The harmonic emissions of different PV-inverters of about 2000W were examined under laboratory conditions with simulated harmonic distortion of the grid voltage and with grid impedance, as shown in fig. 3. This will allow an estimate of the amount of harmonic distortion of the grid voltage by application of PV-inverters.

The PV-inverters connected to a PV- and grid-simulator were separately quantified with the following aspects:

- operating at about maximum output power level
- operating on a clean grid as well as on a grid polluted with harmonic voltages
- operating on a grid without impedance as well as on a grid with impedance.

Measurements on a simulated grid without impedance were used for assessment of the inverters harmonic current emission. Measurements on a simulated grid with impedance were used for assessment of the inverters harmonic interaction with the grid.

During the harmonic measurements the following steps were followed:

- measurements on a clean grid without impedance
- measurements on an average polluted grid (3%THD) without impedance
- measurements on a maximum polluted grid (8% THD) without impedance
- measurements on a clean grid with impedance
- measurements on an average polluted grid (3%THD) with impedance
- measurements on a maximum polluted grid (8% THD) with impedance.

The following step was to focus on resonance of the grid inductance together with the output capacitance of the inverter under test. During inverter-grid resonance search and observation, the following steps were followed:

- the impedance of the grid was doubled in order to observe the effect on the resonance, this was done on a clean grid
- the output power of the inverters was reduced to 50% and 10% in order to observe possible effects.

For simulation of the total of capacitance of domestic equipment, a capacitance of 3 microfarad per home was used. This average value was the outcome of a calculation, done in a Dutch research project [3].

In this investigation an average (3%THD) and a maximum (8%THD) polluted grid voltage were defined, see Fig. 4 and 5. Both grid pollutions were complying with the EN50160. For measurements with a simulated grid without impedance no external impedance was added to the grid simulator, this results in negligible impedance. The grid impedance was build out of a resistor in series with an inductor, see Fig. 3.

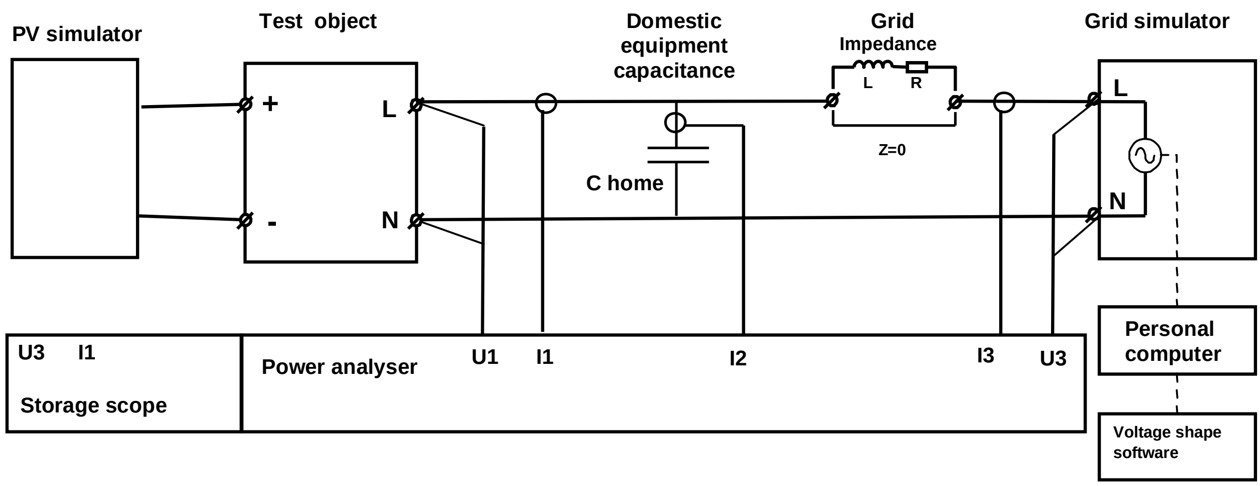

Fig. 3, Test set-up for the laboratory measurements.

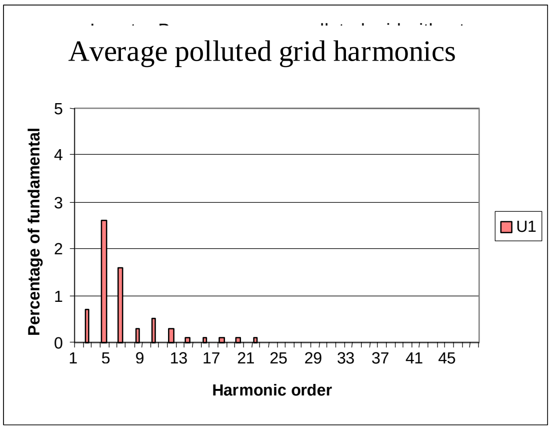

Fig. 4, harmonics of the average polluted grid voltage.

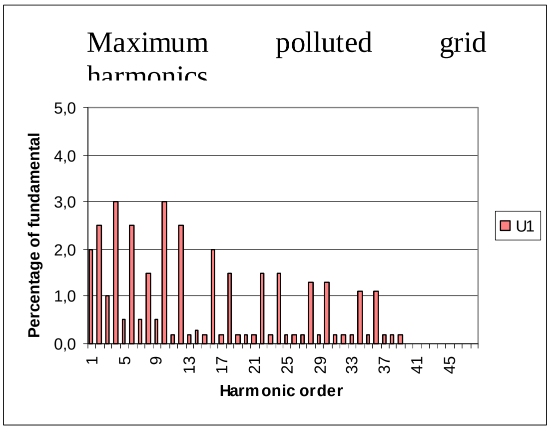

Fig. 5, harmonics of the maximum polluted grid voltage.

In order to simulate the operation of a number of inverters in parallel, measurements were made with the value of a practical grid impedance scaled up by a factor corresponding to the number of inverters. This assumes all the inverters operate identically and feed into a single node. Normally component tolerances, power variations, and the fact that the inverters do not have a single point of coupling will result in a certain amount of averaging, or cancellation, of harmonics, hence the results here represent the worst case situation [4], [5].

A practical value of the inductance of the grid, measured at a home connection can be 0.05 mH. To make this value more practical for the laboratory measurements, a scale factor of 20 was chosen, therefore the simulated value of the grid inductance was 1mH. So the results on harmonic voltage pollution stands for the situation of twenty home connections in parallel on the public grid [3], [4] and [5].

The following figures represent test results of one of the tested inverters. The output capacitance of this inverter was about 6 µF.

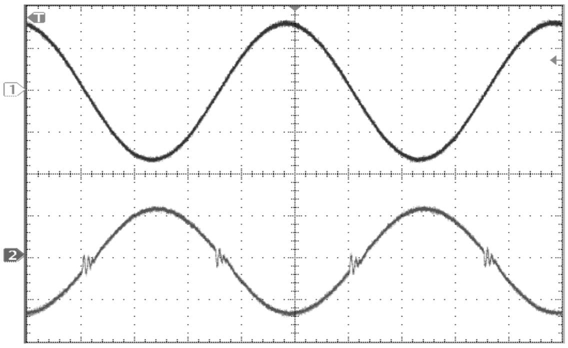

Fig. 6:Measurement on a clean grid without impedance.
1: grid simulator voltage (U3), 2: inverter current (I1).

From the measurement results, as shown in Fig. 6, zero-crossing distortion can be noticed.

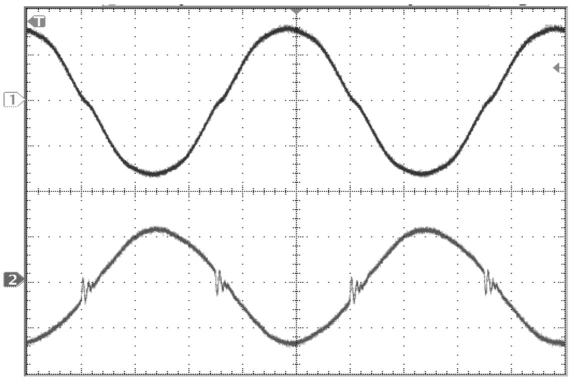

Fig. 7:Measurement on an average polluted grid without impedance.
1: grid simulator voltage (U3), 2: inverter current (I1).

In Fig. 7, slightly more zero-crossing distortion as in Fig. 6 can be noticed as a reaction on the voltage pollution.

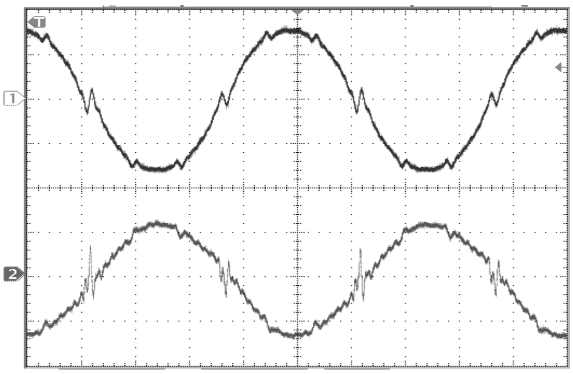

Fig. 8:Measurement on a maximum polluted grid without impedance. 1: grid simulator voltage (U3), 2: inverter current (I1).

In Fig. 8, more zero-crossing distortion as well overall distortion can be noticed as a reaction on the voltage pollution. A part of this distortion is caused by the inverters output capacitor, however it was noticed that more harmonics were present than just the polluted numbers.

Results from measurements with a simulated grid impedance showed a resonance phenomenon between the network and the PV inverter. As figure 9 and 10 shows, this resonance occurs after every zero-crossing.

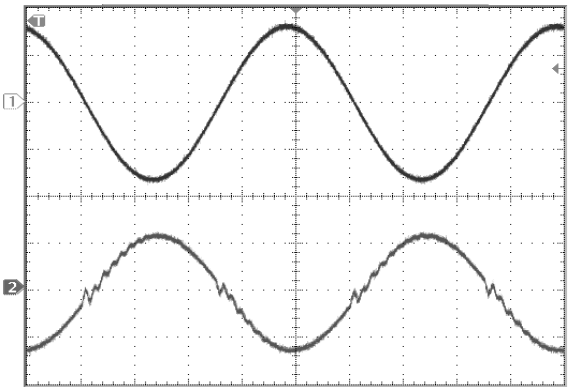

Fig. 9:Measurement on a clean grid with impedance.
1: grid simulator voltage (U3), 2: inverter current (I1).

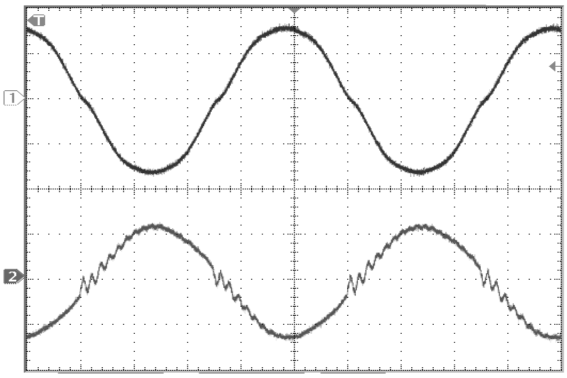

Fig. 10: Measurement on an average polluted grid with impedance.
1: grid simulator voltage (U3), 2: inverter current (I1).

Resonances are enhanced by the grid voltage disturbances, as can be seen in Fig. 11. The distortion can partly attributed to the inverters output capacitor, however it was calculated that the non-ideal current-source character of the inverter caused higher distortion levels. The harmonic pollution of the total grid current in this situation is presented in Fig. 12.

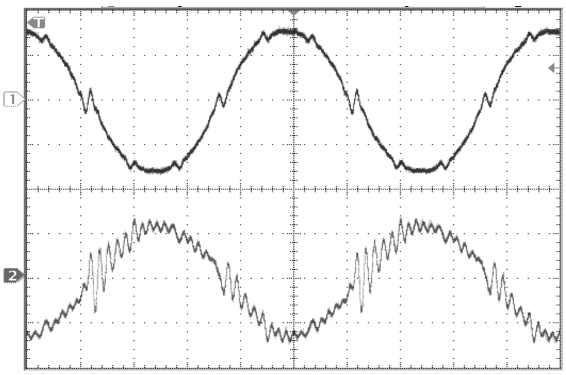

Fig. 11: Measurement on a maximum polluted grid with impedance.
1: grid simulator voltage (U3), 2: inverter current (I1).

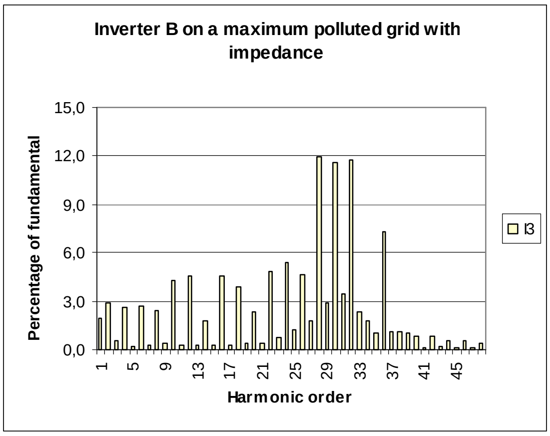

Fig. 12: harmonic pollution of the total grid current I3.

From the experimental laboratory results, an estimate of the resonance frequency can be calculated by:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

where:

f_r - Resonance frequency (Hz)

L - Network reactance (H),
Network distribution transformer reactance in series with the cable reactance to the PV inverters

C - Network Capacitance (F),
Equivalent household capacitance of all the connected houses in parallel $n*C_{house}$, also in parallel with all the real PV inverter output capacitances $m*C_{PV\text{-}Inv}$, n the number of households and m the number of inverters.

The output capacitance of the PV inverter during operation may differ from the measured or specified output capacitance. The real capacitance during operation should be considered here. Due to the current feedback controller the operational capacitance of the inverter is in most cases lower than the real included component values.

Fig. 12 shows a dominant resonance around the 31 harmonic, the expected resonance for a similar situation in practice can be calculated as follows:

- Combination of transformer and cable reactance's: L = 50 µH
- Equivalent household capacitance of 20 homes: C= 60 µF
- PV Inverter capacitance (6 µF) of 20 pieces C=120 µF.

The most dominant resonance frequency f_r: $f_r = \frac{1}{2\pi\sqrt{LC}} = 1{,}68\ kHz \approx 33\ harmonic$.

This result can be confirmed from the lab measurement result of fig. 12.

5. CONCLUSIONS

A resonance phenomenon between the network and PV inverters can be responsible for higher than expected distortion levels in networks. The topology and especially the current control of an inverter have a large influence on the initiation and size of the resonance.

From measurements and calculations the following conclusion could be stated:

- the harmonic current pollution of inverters depends on the voltage pollution of the grid.
- some inverters produce higher than expected current harmonics, simply calculated from the output capacitance of the inverter.
- the total capacitance of the inverter, together with the domestic equipment capacitance as equivalent capacitance, and the reactance of the grid forms the equivalent inductance to form the resonance circuit.

References

[1] EN 50160 Voltage characteristics of electricity supplied by public distribution systems

[2] IEC 61000-3-2 Limit for harmonic current emissions (equipment input current • 16A per phase)

[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" Report KEMA / ECN 40210004 TDC 02-29719A

[4] P.J.M. Heskes, J.F. Groeman, M.J. Jansen, "Harmonic interaction between PV-inverters in parallel and their effects on the voltage distortion". Report: ECN-CX--01-025

[5] A. Kotsopoulos, P.J.M. Heskes, M.J. Jansen, "Zero-Crossing Distortion in Grid-Connected PV Inverters", IECON'02