HARMONIC BEHAVIOR OF TWO COMMERCIAL PV CONVERTERS UNDER DISTORTED VOLTAGES

Michèle DE WITTE
Laborelec – Belgium
michele.dewitte@laborelec.com

Yann PANKOW
Laborelec – Belgium
yann.pankow@laborelec.com

Frédéric COLAS
L2EP - France
frederic.colas@ensam.eu

ABSTRACT

A harmonic converter model was developed in [1] to know the behavior of the converter when the grid contains low-frequency harmonics (< 2kHz). To verify the simulation results, an experimental validation was made based on two commercial PV converters (SMA and Fronius). These converters should be connected to the grid with a voltage containing the fundamental and a harmonic. This harmonic is to be controlled in amplitude and phase, which is very difficult in a classic experimental test; this is why L2EP's (Laboratoire electrotechnique et d'electronique de puissance de Lille) technological platform with real-time simulator grid was used.

INTRODUCTION

Generally, the levels of harmonic currents of different inverters are given by the constructors for a "clean" grid, this means a purely sinusoidal and balanced grid.
In [1] simulations have been executed (Matlab Simulink) to try to see if the functioning of the converter is disturbed when harmonic voltages are present on the grid voltage, we will thus determine the levels of the harmonic currents injected into the grid as a consequence of an initial harmonic pollution of the grid voltage.
The simulations have been done for single phase inverters with an L and an LCL filter, for each of them different powers have been considered (P_{nom} and $P_{nom}/2$).
The results of the simulations showed that the current waveform delivered by the photovoltaic converter was disturbed when harmonics of low frequency were present on the voltage. Harmonic currents appeared in the current that was injected to the grid.

To verify these results obtained by simulations, we decided to proceed with some tests on converters that are on the market . Measurements have been carried out on a converter of SMA and on a Fronius converter. The control of the harmonic voltages in phase and in amplitude being rather difficult, the tests have been performed on the technological platform in real time calculation of L2EP.
The first part of the article will briefly present the technological platform of L2EP as well as some technical considerations relative to the measurements.
In the second part, a descriptive analysis of the obtained measurement results will be proposed and finally the main conclusions will be presented.

TECHNOLOGICAL PLATFORM

The technological platform is used to study the behavior of the electrical power systems of the future. It wants to be an answer to the technological and scientific limitations that are a direct consequence of the mutations in the electrical grids. It serves as a pedagogic and research support for studies concerning the coordination of the production of different kinds of energy sources.

It also integrates a real-time RTLab simulator at the centre of the system. This real-time simulator can be connected with real equipments by means of power amplifiers. The simulation and emulation perspectives of grids become almost unlimited : it will be possible to take into account – in an experimental way – the grid impedances that tie together the different elements of a multi-source production unit and geographically dispersed production units.

Today, it puts together units of different nature: production units (a photovoltaic production unit of 18 kWc), energy storage units (super capacitors) or loads as well as static or dynamic emulation units of different nature (windmill emulator, etc.).

The use of the technological platform allows:

- a personnel and time gain to execute a study
- working in complete security
- the easy realization of difficult tests
- a real reliability of the obtained results

For these tests, the technological platform has been used in a simple way and using only an infinitesimal part of its capabilities. The synoptic representing the interactions between the real and simulation equipments is represented in Figure 1.

Three parts are necessary to execute the different tests :

- The converter under test
- The power amplifier
- The real-time simulator

For the tests, the two converters are used at their maximum power. The DC side of the converter is connected to a continuous power source that is adjustable in voltage as well as in current (not represented in Figure 1). The AC side of the converter is connected to a linear power amplifier. The amplifier has a linear technology , is three phased and has a rated power of 15 kVA with a phase-to-neutral voltage of 400 V. In steady-state the current can go up to 40 A, with a possibility of a peak current of 120 A during 4 seconds. The bandwidth is above 10 kHz.

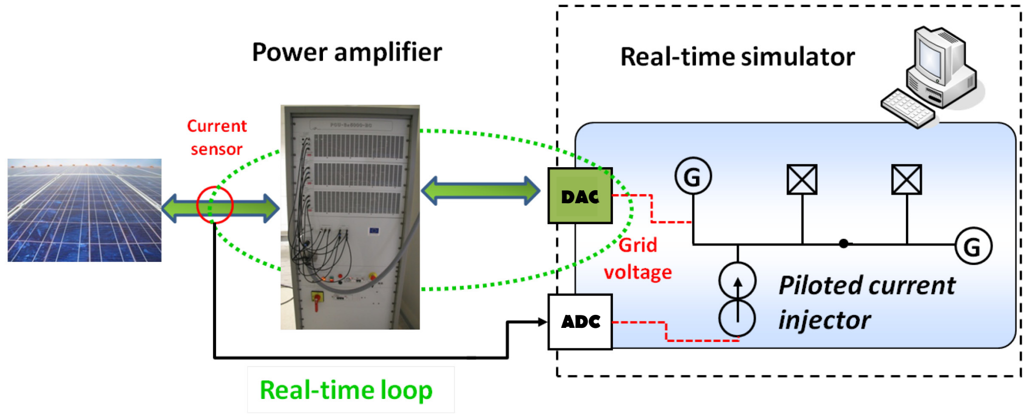


Figure 1: Synoptic of the test platform

It offers thus the possibility to realize a homothetic relation for the power if necessary whilst letting through the harmonics of interest to us, here of a rank lower than 20.

For our measurements only the single phase connection is used and the amplification function is 1 (the real power delivered by the converter).
The precision of the current generator on the DC side is 100 mA; the precision of the voltage generator on the AC side is 0.5 V; the angular precision of the harmonic voltages generator is maximum 0.25°. The voltage measurements have a precision of 150 mV, the current measurement have a precision of 100 mA.
This amplifier is connected to the real-time grid simulator by means of a ADC (numerical – analog and analog – numerical converter.

Supplementary information is exchanged by means of current sensors to put the regulation loops into action in real time.
The real-time simulator allows to simulate any kind of grid, in this case it is a single phase low voltage grid at 230V that has been chosen. It is possible to control the amplitude and the phase of the voltage harmonics of the grid.

MEASUREMENTS

Choices to make

Single phase network
The measurements were performed on a single phase inverter. All the harmonics of the simulation were covered; and all percentages (2, 4, 6, 8 and 10%) too, even though 8% and 10% are fairly high for a real-life situation.

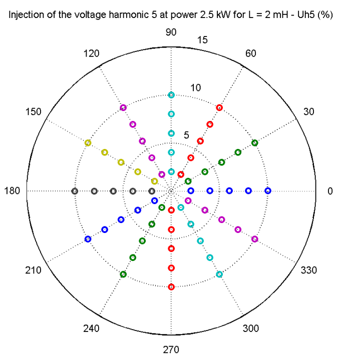


Figure 2: injection of the 5th voltage harmonic to the ideal grid voltage

The delta for the angles was doubled from 30° to 60° as shown in Figure 2.

Measurements to be executed
The aim is to have different measurements for the different configurations mentioned here above.

- First of all, the current injected in the grid must be measured and their amplitude and phase must be analyzed
- Also, an image of the grid voltage must be obtained (for the tests, the voltage contained the fundamental and one harmonic of variable amplitude and phase)
- The voltage at the exit of the inverter should only have a harmonic component identical to the one superposed to the grid voltage. This voltage should also be measured

Inverters used

Two inverters were used for the test, one of SMA and one of Fronius Figure 3. Due to the low powers of these inverters, measurements were only carried out at the nominal power.

The SMA inverter “Windy Boy” has a nominal power of 1 kW; it was operated at 230 V and approximately 4 A (AC side).
The Fronius inverter, with a nominal power of 2.5 kW, was operated at 230 V and approximately 10 A (AC side);

The tests have been performed on these types of converters because they were already used in the laboratory. The choice of the make and the nominal power was limited.

ENCOUNTERED PROBLEMS

Two kinds of problems were encountered during the measurements with the Fronius converter. No problems were encountered with the Windy Boy.

First, for different harmonics at different angles, the

Fronius converter lost synchronization, but was able to be reconnected to the grid again. The combinations of harmonic rank, amplitude and phase are indicated in green in the subsequent Table 1.
Also, for some harmonics it was impossible to synchronize the converter with the grid. These cases, all at 10% of harmonic voltage injection, are indicated in blue in Table 1. In fact is it for the injection of the 13th and the 15th harmonic at 10% and for all angles.

Table 1: Overview of synchronization problems

Harmonic	3	3	5	5	7	7	7	7
Level (%)	8	10	2	10	2	8	10	10
Phase (°)	60	60	0	60	0	240	60	240
Harmonic	9	9	9	11	11	11	11	13
Level (%)	2	10	10	2	10	10	10	10
Phase (°)	0	120	180	0	0	240	300	0
Harmonic	13	13	13	13	13	15	15	15
Level (%)	10	10	10	10	10	2	8	8
Phase (°)	60	120	180	240	300	60	0	180
Harmonic	15	15	15	15	15	15		
Level (%)	10	10	10	10	10	10		
Phase (°)	0	60	120	180	240	300		

Let's take a closer look at some of the cases. For instance, when we look at the results when adding the 7th voltage harmonic to the grid voltage at 8% and 240°, the THDi is 21.29 %, at 10% and the same angle, it becomes 28.56%. In both cases there are problems with synchronization.
When we add the 13th harmonic to the grid voltage at 8% and 120°, we have a THDi of 23.90%. When we go up to 10% of this harmonic, we cannot synchronize the converter:. The THDi has become too big to be able to synchronize the equipment.

The first observation we can make is that the converter with the smallest power (Windy Boy) is not sensitive to the quality of the grid voltage. It connects and remains connected even when the waveform of the voltage is very distorted.

ANALYSIS OF THE RESULTS

Ideal grid voltage

The first thing we looked at, was the generation of the harmonic currents when the grid voltage is ideal, i.e. perfectly sinusoidal.

Figure 3 shows the generated harmonic currents for an ideal voltage for the Windy Boy. In fact, the second current harmonic is the highest. Current harmonics 3 to 8 are all above 1%. The total THDi is 5.26%. The level of the even harmonics is rather astonishing.

Figure 4 also shows the generated harmonic currents for an ideal voltage, but this time for the Fronius converter. Here, we can clearly see that the third current harmonic is the highest; at more than 3%. The total THDi in this case is 3.60%. All other current harmonics are below 1%.

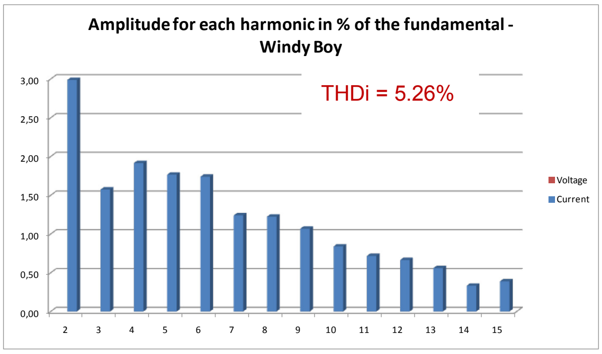


Figure 3: Amplitude for all current harmonics when the grid voltage is ideal for the Windy Boy converter

Even though the Windy Boy has a worse THDi when the grid is "clean", the previous paragraph proves that it is the one with the least problems with synchronization.

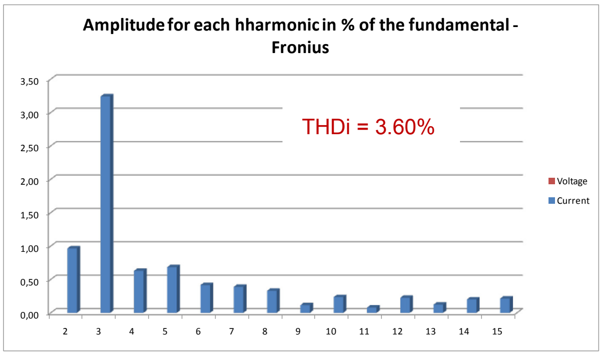
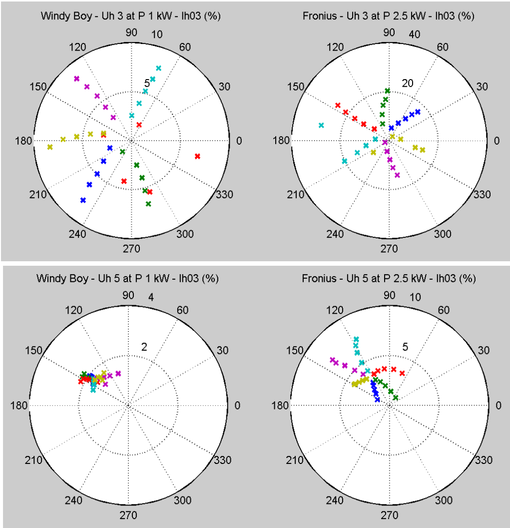


Figure 4: Amplitude for all current harmonics when the grid voltage is ideal for the Fronius converter

Distorted grid voltage

When superposing any harmonic to the ideal grid voltage, the simulation always resulted in a cluster of points for the third harmonic current, situated around 15% at an angle of 270°. However, for the measurements we have different results. When adding the third harmonic (uh3), the measurements form a spider-web-like cluster of points, centered around 0% and 0°, and going up to 30 % as shown in Figure 57 (a).
When adding a 5th harmonic (uh5), we get a smaller spider-web that is off-centre at 120°. For the other voltage harmonics, we have a rather linear cluster of points also at an angle of 120°% as shown in Figure 57 (b).
Let us take a closer look at one of the points of the upper left graph (Figure 57 (a)), in this case we will take a look at the influence of the superposition of the 3rd voltage harmonic at 10% and an angle of 240° on the harmonic currents generated by the converter Windy Boy.
This gives us as a result a 3rd harmonic current of 8.4% ° (point in the upper left corner of the graph, magenta). We can see what other harmonic currents are generated by this converter.

(a)


(b)

Figure 5: Measurement of ih3 when injecting uh3 (a) and uh5 (b)

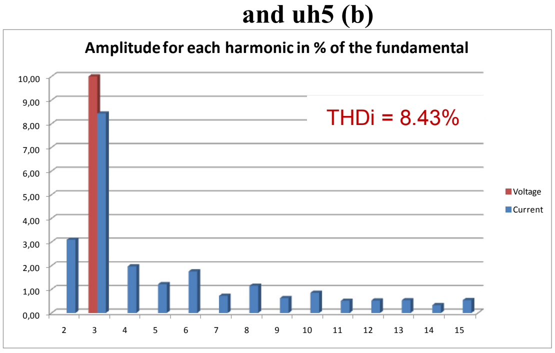


Figure 6: Amplitude for all current harmonics when adding the 3rd harmonic at 10% and an angle of 240°

An interesting result for the Windy Boy is that the phase and the amplitude of the 5th harmonic of the voltage have very little influence because the resulting harmonic currents (Figure 5 7(b)) remain concentrated around a point close to the point for a clean grid (Figure 3).

Now, when looking at the points of the lower right graph. The influence of the angle of the superposed harmonic voltage on the resulting harmonic currents generated by the converter of Fronius can be observed. When adding the fifth harmonic to the grid voltage at 10%, and with the angles 60° and 240°, we obtain two completely different results for the generated 3rd harmonic current. In case of the 60° angle, we have an amplitude of approximately 1% at an angle of about 50° and a total THDi of 20%. For the 240° injection angle, we have an amplitude of 7.34% at an angle of about 140°.
When superposing the harmonic voltage of rank k (uhk) to the ideal grid voltage,. The measurements will always result in a bent spider-web result, albeit a bit bent. This can be observed in Figure 7.
On top of that, we can also remark that when adding uhk to the grid voltage, the resulting ihk for a Windy Boy and a Fronius will be rotated by 140°. This can be observed in Figure 7, where the measurements that correspond with harmonic voltages at a certain angle are aligned on 60° for the Windy Boy converter and on 200° for the Fronius converter. In these two figures we can also clearly see that the delta of 60° for the harmonic voltages is not perfectly maintained in the injected harmonic currents. Sometimes it is difficult to “see” the spider-web in the measurements, especially for the 3rd harmonic (Figure 5).

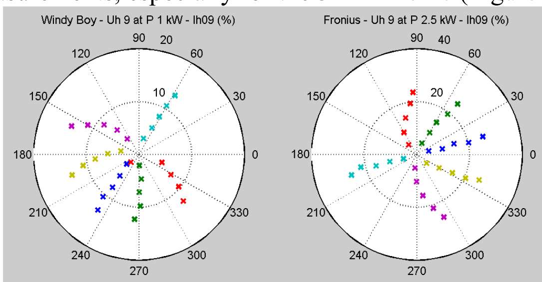


Figure 7: Results for ihk when adding uhk

In general, the results for the measured currents for the Fronius converter are always in a spider-web form, no matter which harmonic voltage is added to the grid voltage and no matter which current harmonic is being looked at. Without really being able to be compared, the percentages of the amplitude of the Windy Boy are generally lower than these of the Fronius. This can be due to the difference in nominal power, but also to the quality of the exit filters.

CONCLUSIONS

When looking at the results of the measurements, we can observe that the harmonic current response of the converters depends strongly on the phase of the voltage harmonic that was added to the ideal grid voltage. Not only the angle of the harmonic current injected in the grid depends on these angles, but even the level of the harmonic currents is influenced by the voltage harmonic’s angle.
The quality of the LCL output filter of the converter has a big influence on the quality of the current injected in the grid. We can clearly see that the results for the Windy Boy converter are (much) better than for the Fronius inverter. All results remain under the limits ([2],[3]).

REFERENCES

[1] Michèle De Witte, Yann Pankow, Emmanuel De Jaeger, 2009, "Study of the harmonic behavior of PWM converters under distorted voltages", *Proceedings CIRED 2009, Paper 0456*, CIRED.
[2] IEC 61000-3-2 – Electromagnetic compatibility (EMC) Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤ 16A per phase)
[3] IEC 61000-3-12 – Electromagnetic compatibility (EMC) Part 3-2: Limits – Limits for harmonic current produced by equipment connected to public low voltage systems with input current > 16A and ≤ 75A per phase.