# PRELIMINARY TESTS RESULTS ABOUT E-CAR HARMONIC EMISSIONS

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## *ABSTRACT*

*The increasing number of electric cars present in our cities goes to analyze the impact that these vehicles have on the distribution network.*
*The collaboration of Enel in the European project "Green E-Motion" has led to the construction of a laboratory measurement at the Enel Test Center of Milan. The laboratory allows on-the-field test for the evaluation of different characteristics of system voltage and absorbed current during charging of electric vehicles.*
*In this paper the results of several measurements are discussed: in particular about the effects of the contemporaneously charging of different electric vehicles.*

## INTRODUCTION

The Enel vision of Smart Grid include the electric vehicles charging station (EVCS) as a fundamental component of the future distribution network; because of that, Enel Distribuzione (ED) is working on several pilot installations in Italy.
In particular, ED was one of the first player in the world to present is own electric vehicles charging platform (EVCP), that now is in operation in Italy and Spain [1].
The recharge of an electric vehicle (EV) require a conversion from AC (energy in the network) to DC (energy in the battery).
The power convertors are non-linear loads and, frequently, are a component of the EVs, so the Distribution System Opeartor (DSO) do not have the responsibility of this power conversion. In other hands, the DSO is the responsible of the quality of the voltage (according to EN 50160) and the characteristics of the current absorbed by the EVCS can create important effect on the system voltage. In this paper the harmonic pollution is addressed.
The IEC 61851-21 established that harmonic limits for the AC input current of EVs are covered by IEC 61000-3-2 (for rated current less than 16 A) and by the IEC 61000-3-12 (for rated current up to 16 A); but an important discussion is in progress about the effectiveness of this constraints.
Two problems have to be well addressed:

- the EVCSs can be a single point of deliverable, but they can recharge several EV contemporaneously, the respect of the limits per EV do not give any warranty to the DSO;
- the harmonic phases have not limits, so it is possible that several model of EV adopt same power convertors, with the risk to have similar harmonics phases.

In order to analyze these problems, ED is monitoring the characteristics pf the recharge of all the EVs compatible with ED EVCS.
In this paper the preliminary results of this activity are described and discussed.

## PRELIMINARY TESTS RESULTS

The results presented in this chapter regard the single-phase charging process for several different EVs (the name of the different EVs tested is not reported in the paper for confidentiality reason).
The charging power have been changed during the charge, 4 steps was adopted:

1. 1.3 kW (230 V – 6 A approximately);
2. 2.3 kW (230 V – 10 A approximately);
3. 2.6 kW (230 V – 12 A approximately);
4. 3 kW (230 V – 14 A approximately).

Each step was at least of 1 h, because during the preliminary tests was observed that some current harmonics have a transient peak in the start of the charge.
In this chapter the followings measured greatness will be discussed:

- amplitude of the harmonics;
- phase of the harmonics;
- THD.

### The adopted instruments

Into the Enel Test Center of Milan was installed a laboratory measurement consists of one ED EVCS, monitorized by two separate measuring chains.
The first chain consists of a TeamWare Equa 2000 class B meter and a second by TeamWare Wally A class A meter [2], both with transducers adequate to the respective classes (according to the IEC 61000-4-30).
Given the absence of the harmonics phases measurement capability in the Wally A instrument (the phase of the harmonics is not considered among the parameters of the power quality in the IEC 61000-4-30), the measurements taken by the Equa 2000 are used in this paper. The Wally A was used for the validation of the class B measurement chain, whose measures have fallen inside the range of its intrinsic uncertainty. The voltage and current amplitude and phase, for all the harmonics ≤ 25° order, were monitored in the tests.

### Amplitude of the harmonics

The IEC 61851-21 established that harmonic limits for the AC input current of EVs (with rated current less than 16 A) are covered by IEC 61000-3-2 (figure 1).
In figure 2 the results of the measurements is represented:

- the 4 power steps are present (step 1 – blue, step 2 – rose, step 3 – green, step 4 – white);
- the values are in percentage with respect to the limits (figure 1);
- all the 25 harmonics order are showed;
- in the first column the highest value of the cluster is represented.

| Harmonic order<br>n | Maximum permissible harmonic current<br>A |
|---|---|
| **Odd harmonics** | |
| 3 | 2,30 |
| 5 | 1,14 |
| 7 | 0,77 |
| 9 | 0,40 |
| 11 | 0,33 |
| 13 | 0,21 |
| $15 \le n \le 39$ | $0,15 \frac{15}{n}$ |
| **Even harmonics** | |
| 2 | 1,08 |
| 4 | 0,43 |
| 6 | 0,30 |
| $8 \le n \le 40$ | $0,23 \frac{8}{n}$ |

Figure 1: Limits for EV on the IEC 61000-3-2

For example, with reference to the first 2 steps of the 5° harmonic:

- in the first step, the 26,2% of the measures for all the EV was between 0% and 10% of the limits, the 23,8% of the measures for all the EV was between 10% and 20% of the limits and the 50% of the measures for all the EV was between 20% and 30% of the limits;
- in the second step, the 36% of the measures for all the EV was between 0% and 10% of the limits, the 57% of the measures for all the EV was between 10% and 20% of the limits and the 7% of the measures for all the EV was between 20% and 30% of the limits.

| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **10** | 100 | 0 | 100 | 26,2 | 100 | 5,81 | 100 | 0,58 | 100 | 2,91 | 100 | 1,16 | 99,4 | 1,74 | 98,8 | 17,4 | 99,4 | 2,33 | 98,8 | 0 | 98,8 | 0 | 99,4 | 4,65 |
| **20** | 0 | 25 | 0 | 23,8 | 0 | 52,3 | 0 | 24,4 | 0 | 32,6 | 0 | 8,72 | 0,58 | 20,3 | 1,16 | 33,1 | 0,58 | 33,7 | 1,16 | 48,3 | 1,16 | 39 | 0,58 | 68 |
| **30** | 0 | 0 | 0 | 50 | 0 | 41,9 | 0 | 25 | 0 | 64,5 | 0 | 57,6 | 0 | 47,7 | 0 | 32 | 0 | 55,8 | 0 | 12,8 | 0 | 37,2 | 0 | 25 |
| **40** | 0 | 75 | 0 | 0 | 0 | 0 | 0 | 50 | 0 | 0 | 0 | 9,3 | 0 | 11,6 | 0 | 16,3 | 0 | 8,14 | 0 | 20,3 | 0 | 2,33 | 0 | 2,33 |
| **50** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16,9 | 0 | 10,5 | 0 | 1,16 | 0 | 0 | 0 | 18,6 | 0 | 7,56 | 0 | 0 |
| **60** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6,4 | 0 | 5,81 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9,88 | 0 | 0 |
| **70** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4,07 | 0 | 0 |
| **80** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **90** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **100** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **10** | 100 | 0 | 100 | 36 | 100 | 25,6 | 100 | 0 | 100 | 0 | 100 | 0 | 100 | 8,14 | 100 | 0 | 100 | 0 | 98,8 | 0 | 100 | 0 | 97,7 | 0 |
| **20** | 0 | 50 | 0 | 57 | 0 | 64 | 0 | 0 | 0 | 17,4 | 0 | 14 | 0 | 43 | 0 | 0 | 0 | 0 | 1,16 | 0 | 0 | 0 | 2,33 | 0 |
| **30** | 0 | 0 | 0 | 6,98 | 0 | 10,5 | 0 | 0 | 0 | 73,3 | 0 | 33,7 | 0 | 25,6 | 0 | 27,9 | 0 | 0 | 0 | 12,8 | 0 | 1,16 | 0 | 15,1 |
| **40** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 81,4 | 0 | 9,3 | 0 | 24,4 | 0 | 19,8 | 0 | 46,5 | 0 | 38,4 | 0 | 74,4 | 0 | 64 | 0 | 55,8 |
| **50** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 18,6 | 0 | 0 | 0 | 11,6 | 0 | 3,49 | 0 | 25,6 | 0 | 46,5 | 0 | 12,8 | 0 | 33,7 | 0 | 29,1 |
| **60** | 0 | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16,3 | 0 | 0 | 0 | 0 | 0 | 15,1 | 0 | 0 | 0 | 1,16 | 0 | 0 |
| **70** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **80** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **90** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **100** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **10** | 100 | 0 | 100 | 1,55 | 100 | 16,3 | 100 | 7,75 | 100 | 28,7 | 100 | 0 | 100 | 2,33 | 100 | 0,78 | 99,2 | 0 | 96,1 | 1,55 | 87,6 | 0 | 79,8 | 11,6 |
| **20** | 0 | 33,3 | 0 | 25,6 | 0 | 48,1 | 0 | 36,4 | 0 | 38 | 0 | 0 | 0 | 16,3 | 0 | 22,5 | 0,78 | 1,55 | 3,88 | 11,6 | 11,6 | 2,33 | 19,4 | 14 |
| **30** | 0 | 0 | 0 | 27,1 | 0 | 2,33 | 0 | 22,5 | 0 | 31,8 | 0 | 0,78 | 0 | 39,5 | 0 | 17,1 | 0 | 12,4 | 0 | 18,6 | 0,78 | 28,7 | 0,78 | 6,98 |
| **40** | 0 | 11,6 | 0 | 45,7 | 0 | 0,78 | 0 | 20,2 | 0 | 1,55 | 0 | 10,1 | 0 | 41,1 | 0 | 30,2 | 0 | 14 | 0 | 16,3 | 0 | 21,7 | 0 | 9,3 |
| **50** | 0 | 55 | 0 | 0 | 0 | 31,8 | 0 | 13,2 | 0 | 0 | 0 | 41,1 | 0 | 0,78 | 0 | 26,4 | 0 | 14 | 0 | 44,2 | 0 | 32,6 | 0 | 45 |
| **60** | 0 | 0 | 0 | 0 | 0 | 0,78 | 0 | 0 | 0 | 0 | 0 | 31 | 0 | 0 | 0 | 2,33 | 0 | 19,4 | 0 | 7,75 | 0 | 14 | 0 | 13,2 |
| **70** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16,3 | 0 | 0 | 0 | 0 | 0 | 4,65 | 0 | 0 | 0 | 0,78 | 0 | 0 |
| **80** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,78 | 0 | 0 | 0 | 0 | 0 | 10,1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **90** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,78 | 0 | 20,2 | 0 | 0 | 0 | 0 | 0 | 0 |
| **100** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3,88 | 0 | 0 | 0 | 0 | 0 | 0 |
| **10** | 89 | 0 | 98,3 | 1,74 | 93 | 6,4 | 86,6 | 0 | 95,9 | 0 | 95,3 | 11 | 93,6 | 1,74 | 96,5 | 0 | 91,9 | 0 | 93,6 | 0 | 92,4 | 0 | 93 | 1,16 |
| **20** | 11 | 0 | 1,74 | 43,6 | 6,98 | 31,4 | 13,4 | 20,3 | 4,07 | 14,5 | 4,65 | 14 | 6,4 | 23,8 | 3,49 | 0,58 | 8,14 | 0 | 5,81 | 0 | 7,56 | 0,58 | 6,98 | 23,3 |
| **30** | 0 | 0 | 0 | 6,4 | 0 | 12,8 | 0 | 4,65 | 0 | 17,4 | 0 | 19,2 | 0 | 13,4 | 0 | 3,49 | 0 | 5,23 | 0,58 | 6,4 | 0 | 33,1 | 0 | 22,1 |
| **40** | 0 | 23,8 | 0 | 32,6 | 0 | 12,2 | 0 | 36,6 | 0 | 32,6 | 0 | 27,9 | 0 | 10,5 | 0 | 39 | 0 | 9,88 | 0 | 12,2 | 0 | 18 | 0 | 23,3 |
| **50** | 0 | 51,2 | 0 | 15,7 | 0 | 19,2 | 0 | 13,4 | 0 | 28,5 | 0 | 4,07 | 0 | 19,2 | 0 | 30,8 | 0 | 14,5 | 0 | 53,5 | 0 | 22,1 | 0 | 16,9 |
| **60** | 0 | 0 | 0 | 0 | 0 | 17,4 | 0 | 6,98 | 0 | 6,98 | 0 | 1,74 | 0 | 9,3 | 0 | 4,65 | 0 | 37,2 | 0 | 27,9 | 0 | 23,8 | 0 | 12,8 |
| **70** | 0 | 1,16 | 0 | 0 | 0 | 0,58 | 0 | 15,7 | 0 | 0 | 0 | 12,2 | 0 | 18,6 | 0 | 16,3 | 0 | 26,2 | 0 | 0 | 0 | 2,33 | 0 | 0,58 |
| **80** | 0 | 23,8 | 0 | 0 | 0 | 0 | 0 | 2,33 | 0 | 0 | 0 | 9,88 | 0 | 3,49 | 0 | 5,23 | 0 | 5,23 | 0 | 0 | 0 | 0 | 0 | 0 |
| **90** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,74 | 0 | 0 | 0 | 0 | 0 | 0 |
| **100** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 2: Amplitude of the harmonics with respect to the limits

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | 0 | 3,68 | 0 | 3,68 | 0 | 5,79 | 0 | 4,21 | 0 | 3,16 | 25,3 | 3,68 | 16,3 | 10 | 36,8 | 4,21 | 2,63 | 6,32 | 11,6 | 5,79 | 17,9 | 6,32 | 16,8 | 7,89 | 0 |
| 60 | 27,4 | 4,21 | 0 | 6,84 | 0 | 7,89 | 0 | 12,1 | 0 | 15,3 | 0,53 | 9,47 | 15,3 | 13,2 | 1,05 | 15,3 | 2,63 | 12,1 | 1,05 | 9,47 | 0 | 9,47 | 0 | 11,6 | 0,53 |
| 90 | 0 | 20,5 | 0 | 17,9 | 14,2 | 14,2 | 14,7 | 25,3 | 0 | 11,1 | 13,2 | 13,2 | 0,53 | 8,42 | 0 | 5,26 | 1,05 | 5,26 | 0 | 4,74 | 0 | 4,74 | 0 | 5,26 | 37,9 |
| 120 | 0 | 10 | 0 | 20,5 | 9,47 | 16,8 | 42,1 | 21,6 | 36,8 | 14,2 | 12,1 | 27,4 | 13,7 | 11,1 | 0 | 3,68 | 1,05 | 4,21 | 0 | 3,68 | 0 | 2,63 | 0 | 1,58 | 10,5 |
| 150 | 0 | 8,42 | 0 | 21,1 | 25,8 | 13,7 | 43,2 | 5,26 | 40 | 10,5 | 22,1 | 18,9 | 13,2 | 13,7 | 11,6 | 13,2 | 0 | 15,8 | 0 | 16,3 | 0 | 13,2 | 13,2 | 9,47 | 12,1 |
| 180 | 0 | 12,1 | 50 | 15,8 | 0,53 | 7,37 | 0 | 15,3 | 0,53 | 14,2 | 2,63 | 4,21 | 1,05 | 3,68 | 15,8 | 13,7 | 0,53 | 9,47 | 0 | 17,4 | 0,53 | 15,3 | 9,47 | 8,95 | 17,9 |
| 210 | 0 | 12,6 | 22,6 | 2,63 | 27,4 | 2,11 | 0 | 8,42 | 22,1 | 15,3 | 0 | 12,6 | 0 | 12,6 | 22,1 | 16,8 | 6,32 | 9,47 | 1,05 | 12,1 | 22,1 | 16,3 | 1,58 | 14,7 | 14,7 |
| 240 | 0 | 8,42 | 20 | 3,68 | 0 | 2,63 | 0 | 2,11 | 0,53 | 3,68 | 0 | 2,63 | 0,53 | 8,42 | 0,53 | 13,2 | 21,1 | 16,8 | 4,74 | 11,1 | 1,05 | 11,1 | 13,7 | 12,6 | 5,26 |
| 270 | 0 | 7,89 | 7,37 | 0,53 | 0 | 6,84 | 0 | 2,11 | 0 | 2,63 | 2,63 | 0,53 | 0 | 8,42 | 0 | 4,74 | 17,9 | 8,42 | 29,5 | 7,37 | 14,2 | 3,16 | 8,95 | 8,42 | 0,53 |
| 300 | 0 | 4,74 | 0 | 2,11 | 6,32 | 6,84 | 0 | 2,63 | 0 | 3,16 | 20 | 2,11 | 0 | 2,11 | 0 | 2,63 | 15,8 | 7,89 | 13,7 | 6,32 | 14,2 | 8,42 | 18,9 | 4,74 | 0 |
| 330 | 0 | 3,68 | 0 | 1,05 | 16,3 | 5,79 | 0 | 0,53 | 0 | 3,16 | 0 | 3,16 | 9,47 | 3,68 | 0 | 4,21 | 2,11 | 2,63 | 5,79 | 2,63 | 23,7 | 5,26 | 10,5 | 6,32 | 0 |
| 360 | 72,6 | 3,68 | 0 | 4,21 | 0 | 10 | 0 | 0,53 | 0 | 3,68 | 1,58 | 2,11 | 30 | 4,74 | 12,1 | 3,16 | 28,9 | 1,58 | 32,6 | 3,16 | 6,32 | 4,21 | 6,84 | 8,42 | 0,53 |
| 30 | 0 | 2,17 | 0 | 0,72 | 29 | 1,45 | 0 | 4,35 | 0 | 7,25 | 0 | 13 | 42 | 20,3 | 32,6 | 18,8 | 1,45 | 13,8 | 0 | 14,5 | 37,7 | 11,6 | 7,25 | 8,7 | 0 |
| 60 | 0 | 11,6 | 0 | 13 | 0,72 | 26,8 | 0 | 23,2 | 0 | 19,6 | 0 | 22,5 | 0 | 18,1 | 16,7 | 5,8 | 25,4 | 4,35 | 37,7 | 2,17 | 0 | 2,9 | 0 | 1,45 | 0 |
| 90 | 0 | 23,2 | 0 | 25,4 | 0 | 15,9 | 4,35 | 15,9 | 0 | 15,9 | 0 | 15,9 | 37 | 11,6 | 41,3 | 10,9 | 10,9 | 6,52 | 0 | 5,8 | 0 | 6,52 | 0 | 5,07 | 0 |
| 120 | 0 | 7,97 | 0 | 20,3 | 27,5 | 19,6 | 60,9 | 28,3 | 0 | 37,7 | 7,97 | 34,8 | 0,72 | 27,5 | 9,42 | 31,2 | 0 | 26,8 | 0 | 25,4 | 0 | 23,2 | 0 | 22,5 | 0 |
| 150 | 0 | 13 | 0 | 6,52 | 41,3 | 9,42 | 34,8 | 10,9 | 51,4 | 6,52 | 56,5 | 7,97 | 0 | 11,6 | 0 | 18,8 | 0 | 24,6 | 0 | 24,6 | 0 | 29 | 0 | 31,2 | 0 |
| 180 | 0 | 3,62 | 38,4 | 9,42 | 0 | 10,9 | 0 | 5,8 | 48,6 | 2,17 | 32,6 | 2,17 | 0 | 3,62 | 0 | 0,72 | 0 | 0,72 | 0 | 1,45 | 0 | 3,62 | 0 | 8,7 | 0,72 |
| 210 | 0 | 5,8 | 61,6 | 6,52 | 0 | 10,1 | 0 | 4,35 | 0 | 0 | 2,9 | 1,45 | 0 | 0 | 0 | 0 | 0 | 0,72 | 0 | 0,72 | 0 | 4,35 | 0 | 0,72 | 29,7 |
| 240 | 0 | 5,07 | 0 | 2,17 | 0 | 4,35 | 0 | 3,62 | 0 | 4,35 | 0 | 0 | 0 | 0,72 | 0 | 0,72 | 0 | 3,62 | 0 | 5,8 | 0 | 1,45 | 34,1 | 0,72 | 29 |
| 270 | 0 | 25,4 | 0 | 7,25 | 0 | 0,72 | 0 | 0,72 | 0 | 1,45 | 0 | 0 | 0 | 0 | 0 | 0,72 | 0 | 2,17 | 0 | 3,62 | 26,8 | 0,72 | 28,3 | 0,72 | 2,9 |
| 300 | 0 | 2,17 | 0 | 4,35 | 0 | 0 | 0 | 0,72 | 0 | 1,45 | 0 | 0 | 0 | 0 | 0 | 1,45 | 0 | 4,35 | 0,72 | 0 | 35,5 | 0 | 0 | 0,72 | 0 |
| 330 | 0 | 0 | 0 | 2,9 | 0 | 0,72 | 0 | 0,72 | 0 | 2,9 | 0 | 0 | 0 | 1,45 | 0 | 5,07 | 18,8 | 0,72 | 38,4 | 3,62 | 0 | 4,35 | 0 | 7,97 | 13 |
| 360 | 100 | 0 | 0 | 1,45 | 1,45 | 0 | 0 | 1,45 | 0 | 0,72 | 0 | 2,17 | 20,3 | 5,07 | 0 | 5,8 | 43,5 | 11,6 | 23,2 | 12,3 | 0 | 12,3 | 30,4 | 11,6 | 24,6 |
| 30 | 0 | 0,53 | 0 | 5,79 | 0 | 1,05 | 0 | 2,63 | 0 | 3,68 | 7,89 | 2,63 | 7,37 | 6,84 | 8,95 | 1,58 | 20 | 3,68 | 7,37 | 0,53 | 0 | 1,05 | 9,47 | 1,05 | 26,3 |
| 60 | 27,4 | 2,11 | 0 | 4,21 | 0 | 2,11 | 0 | 4,74 | 0 | 2,63 | 1,05 | 4,74 | 21,6 | 5,79 | 36,8 | 4,21 | 0,53 | 5,26 | 1,05 | 1,05 | 24,7 | 1,58 | 26,3 | 2,11 | 0,53 |
| 90 | 0 | 11,1 | 0 | 18,4 | 0 | 16,8 | 5,79 | 28,4 | 0 | 24,2 | 0 | 28,4 | 51,1 | 16,8 | 22,1 | 24,7 | 23,2 | 23,7 | 26,3 | 18,9 | 2,63 | 17,4 | 14,2 | 17,4 | 1,05 |
| 120 | 0 | 18,4 | 0 | 10 | 38,4 | 13,7 | 32,1 | 17,9 | 0 | 18,4 | 0 | 24,2 | 20 | 21,6 | 8,42 | 24,2 | 3,16 | 23,2 | 0 | 22,6 | 3,16 | 22,6 | 0 | 22,6 | 27,9 |
| 150 | 0 | 15,8 | 0 | 12,6 | 32,6 | 15,3 | 27,9 | 9,47 | 21,6 | 11,6 | 22,1 | 16,3 | 0 | 4,21 | 0,53 | 4,21 | 0,53 | 4,74 | 1,58 | 5,79 | 19,5 | 5,26 | 17,4 | 7,37 | 0 |
| 180 | 0 | 8,95 | 24,7 | 15,8 | 1,58 | 17,9 | 26,8 | 18,4 | 33,2 | 24,7 | 10,5 | 14,2 | 0 | 21,6 | 0 | 19,5 | 0 | 12,1 | 21,6 | 12,1 | 4,74 | 6,32 | 10 | 4,21 | 3,16 |
| 210 | 0 | 10 | 47,9 | 11,1 | 27,4 | 8,42 | 4,74 | 10 | 35,3 | 3,16 | 37,4 | 5,26 | 0 | 14,7 | 0,53 | 15,8 | 5,79 | 15,8 | 8,42 | 21,1 | 9,47 | 14,2 | 0 | 9,47 | 10,5 |
| 240 | 0 | 7,37 | 27,4 | 4,74 | 0 | 7,37 | 1,58 | 6,84 | 10 | 0 | 2,63 | 0,53 | 0 | 1,05 | 0 | 0 | 16,8 | 1,58 | 15,3 | 7,37 | 10 | 11,1 | 0 | 15,3 | 6,32 |
| 270 | 0 | 21,1 | 0 | 5,26 | 0 | 6,84 | 1,05 | 1,05 | 0 | 1,05 | 0 | 0,53 | 0 | 1,05 | 1,05 | 0 | 8,42 | 2,11 | 3,16 | 0,53 | 3,16 | 1,05 | 0 | 11,6 | 21,6 |
| 300 | 0 | 2,63 | 0 | 4,21 | 0 | 3,68 | 0 | 0 | 0 | 0,53 | 0,53 | 0,53 | 0 | 0,53 | 17,4 | 0,53 | 15,8 | 2,11 | 0 | 1,58 | 4,21 | 9,47 | 22,6 | 7,89 | 1,58 |
| 330 | 0 | 1,05 | 0 | 2,11 | 0 | 3,68 | 0 | 0 | 0 | 3,68 | 4,74 | 1,05 | 0 | 1,58 | 4,21 | 2,63 | 2,63 | 2,11 | 0 | 2,63 | 18,4 | 6,84 | 0 | 0,53 | 0 |
| 360 | 72,6 | 1,05 | 0 | 5,79 | 0 | 3,16 | 0 | 0,53 | 0 | 6,32 | 13,2 | 1,58 | 0 | 4,21 | 0 | 2,63 | 3,16 | 3,68 | 15,3 | 5,79 | 0 | 3,16 | 0 | 0,53 | 1,05 |
| 30 | 0 | 3,31 | 0 | 7,73 | 3,31 | 3,87 | 0 | 2,76 | 0 | 9,94 | 0 | 12,7 | 9,39 | 22,7 | 0 | 16,6 | 8,84 | 12,2 | 22,7 | 10,5 | 6,63 | 5,52 | 23,8 | 2,76 | 12,7 |
| 60 | 28,7 | 9,39 | 0 | 11,6 | 21 | 20,4 | 0 | 23,8 | 0 | 17,7 | 0 | 16 | 2,21 | 9,39 | 3,31 | 1,1 | 17,1 | 6,63 | 0 | 3,31 | 19,9 | 1,66 | 2,76 | 3,31 | 2,21 |
| 90 | 0 | 18,8 | 0 | 14,4 | 3,87 | 3,31 | 2,21 | 4,42 | 0 | 6,08 | 0 | 11,6 | 5,52 | 7,18 | 25,4 | 11 | 0,55 | 11,6 | 18,2 | 6,63 | 8,84 | 8,84 | 0 | 8,29 | 0 |
| 120 | 0 | 16 | 0 | 11 | 14,4 | 11,6 | 48,1 | 13,8 | 0 | 12,2 | 0 | 15,5 | 14,9 | 5,52 | 39,2 | 11 | 23,2 | 8,29 | 18,2 | 4,42 | 0 | 6,63 | 0 | 11,6 | 0 |
| 150 | 0 | 19,9 | 0 | 6,63 | 28,7 | 2,76 | 21 | 8,29 | 19,9 | 24,3 | 21,5 | 17,1 | 36,5 | 9,94 | 7,73 | 14,4 | 28,7 | 8,29 | 16 | 7,18 | 0 | 4,42 | 0 | 2,76 | 0 |
| 180 | 0 | 3,31 | 23,8 | 12,2 | 0,55 | 9,94 | 1,1 | 26 | 37,6 | 22,7 | 26 | 16,6 | 6,08 | 18,8 | 0,55 | 21 | 0 | 24,3 | 0 | 19,9 | 0 | 21 | 0 | 18,2 | 0 |
| 210 | 0 | 0 | 47,5 | 6,63 | 28,2 | 6,08 | 27,1 | 9,94 | 13,8 | 3,31 | 0 | 4,42 | 6,63 | 9,94 | 17,1 | 9,94 | 0 | 13,8 | 0 | 21 | 0 | 22,1 | 0,55 | 24,3 | 0,55 |
| 240 | 0 | 3,31 | 28,7 | 13,8 | 0 | 9,39 | 0,55 | 3,87 | 28,2 | 1,66 | 3,87 | 2,76 | 3,87 | 2,76 | 6,63 | 1,1 | 0 | 1,1 | 0 | 1,1 | 0 | 4,42 | 0 | 6,63 | 14,9 |
| 270 | 0 | 21,5 | 0 | 4,42 | 0 | 8,84 | 0 | 2,76 | 0,55 | 0,55 | 46,4 | 0,55 | 0,55 | 5,52 | 0 | 1,1 | 0 | 0,55 | 0 | 1,1 | 0 | 3,87 | 13,3 | 0 | 30,9 |
| 300 | 0 | 2,76 | 0 | 2,76 | 0 | 7,18 | 0 | 1,1 | 0 | 0 | 2,21 | 0 | 0 | 1,66 | 0 | 2,21 | 0 | 2,21 | 0 | 4,97 | 10,5 | 1,66 | 13,3 | 1,1 | 8,84 |
| 330 | 0 | 0,55 | 0 | 3,31 | 0 | 7,73 | 0 | 2,76 | 0 | 0,55 | 0 | 1,66 | 0 | 2,21 | 0 | 2,76 | 0 | 0 | 2,21 | 5,52 | 19,3 | 7,73 | 34,3 | 8,84 | 17,1 |
| 360 | 71,3 | 1,1 | 0 | 5,52 | 0 | 8,84 | 0 | 0,55 | 0 | 1,1 | 0 | 1,1 | 14,4 | 4,42 | 0 | 7,73 | 21,5 | 11 | 22,7 | 14,4 | 34,8 | 12,2 | 12,2 | 12,2 | 12,7 |

Figure 3: Phase of the harmonics

The results for the step 4 show that the odd harmonics are frequently close to the limits, in particular the 3° harmonic (23,8% of the measures is between 70% and 80% of the limits).
The results for the other steps show that the harmonic pollution do not decrease quickly as the fundamental, for example the 3° harmonic in step 3 have 38.8% as average values and in step 1 have 35%; so the fundamental is the 50% and the 3° harmonic is practically the same.
With reference to the even harmonics the limits are respected largely.

## Phase of the harmonics

The IEC 61851-21 do not fix any prescription for the phase

of the harmonic.
In figure 3 the results of the measurements is represented:

- the 4 power steps are present (step 1 – blue, step 2 – rose, step 3 – green, step 4 – white);
- the values are in degree;
- all the 25 harmonics order are showed (fundamental included);
- in the first column the highest value of the cluster is represented.

The results show that the harmonics phases are frequently very stable for all the steps; for example for the 3° harmonics the interval 150° ÷ 210° contains the 72.6% of the measures for step 1, 100% for step 2, 72.6% for step 3 and 71.3% for step 4.
With reference to the fundamental, the phase is frequently close to 0° or in the sector 330° ÷ 0°; but in step 1 and 3 some EV present inductive behaviour.
With reference to the even harmonics the phases seem to be closer to the "random phase hipotesys", but this harmonics have very little amplitude and the accuracy to a class B instrument is not enough in this case; so these measures are not accurate and no further considerations are possible.

### THD of the currents

The IEC 61851-21 fix an implicit prescription for the THD of the currents ($THD_I$); but starting of the limits in figure 1, it is possible to calculate a limit for the total harmonic current ($thc_I$), that is 3.042 A; so:

$$THD_I = \frac{thc_I}{I_1} = \frac{\sqrt{\sum_{n=2}^{40} I_n^2}}{I_1} = \frac{3.042}{I_1}, \qquad (1)$$

The first analysis of the measures of the $THD_I$ shows that frequently the limit are very far.
But this is a deceptive observation, because the THD is dominated by the 3° harmonics (hits absolute value is enormous to respect to the other ones) and where this harmonics is well "controlled" the $THD_I$ is very far to the limits. However the figure 2 show that also the high order harmonics are frequently close to the limits and the analysis of the $THD_I$ can hide that.

## CONCLUSIONS

In this paper the results of several measurements about the characteristics of the EV recharge current are discussed.
With reference to the harmonics amplitude the measures was frequently close to the limits, but the main topics is that the harmonic pollution is pretty stable when the recharge power is decreased.
This aspect is very important, because to solve the power congestion due to the EV recharging, several times a modulation of the recharge power was proposed; but modulate the power to solve problems in the fundamental regime can create problems with harmonics. Two cars charging at 50% of the nominal power can have harmonic emission strongly higher than a single car charging at the rated power. This aspect suggest to avoid modulation and use an intermittent alternative recharge, so 50% of times for each EV with rated recharge power.
With reference to the harmonics phase the measures indicate a relevant stability for the same EV with respect the modulation of the recharge power, but, also, for different EV.
This aspect tell about the effect of contemporaneous recharge of several EVs. In several paper this problem is studied with the hypothesis that the harmonic phases will assume a random value, because the probability that 2 EV have similar phases, for the same harmonic order, is supposed very rare; but in the present tests, this hypothesis is not verified.
With reference to the THD of the currents, that was proposed in the past as a measure of the harmonic emission, the measures indicate that in some cases the low order harmonics (< 9°) are closer to the limits than the higher order. In this case the THD of the currents is far to the limits, but this cannot be a correct measure of the harmonics pollution.
Finally, the exposed results suggest that the harmonic emissions have to be better arranged by the EV manufacturers, because to improve the charge control part should be several time cheaper for the system, than the effects of uncontrolled emissions in the grid or the installation of the countermeasures by the DSO.

## REFERENCES

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