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An experimental approach for assessing the harmonic impact of fast charging electric vehicles on the distribution systems

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Abstract

Fast charging is perceived by users as a preferential way for electric vehicles (EV) to extend average daily mobility. Fast chargers rated power, their expected operation mostly during peak hours and clustering in designated stations, raise significant concerns. On one hand it raises concerns about power quality standard requirements, especially harmonic distortion due to the use of power electronics connecting to high loads typically ranging from 18-24 kWh, and on the other hand infrastructure dimensioning and design for those investing in such facilities. We performed four sets of measurements during an EV complete fast charging cycles and analysed individual harmonic's amplitude and phase angles behaviour and calculated the voltage and current total harmonic distortion (THD) and Total Demand Distortion (TDD) comparing it with IEEE519, IEC 61000/EN50160 standards. Additionally, we simulated, two vehicles being fast charged while connected to the same feeder, and analysed how the harmonic phase angles would relate. We concluded that the use of TDD was a better indicator than THD since the first one uses the maximum current (IL) and the latter uses the fundamental current, sometimes misleading conclusions, hence suggested to be included in IEC/EN standard updates. Voltage THD and TDD for the analysed charger, were within the standards limitations 1.2% and 12% respectively, however individual harmonics (11th and 13th) failed to comply with the 5.5% limit in IEEE 519 (5% and 3% respectively in IEC61000). Phase angles tended to have preferential range differences from the fundamental. We found that the average difference between the same harmonic order phase angles, are lower than 90°, meaning that when more than one vehicle is connected to the same feeder the amplitudes will tend to add. Since the limits are dependable on the upstream short circuit current (ISC), if the number of vehicles increase (i.e. IL), the standard limits will decrease and eventually are broken. The harmonic limitation is hence a first binding condition, well before the power limitation is. The number of chargers will be limited first not by the power capacity of the upstream power circuit but by the harmonic limits for electric pollution.

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1. Introduction

The paradigm change from centralised unidirectional electricity flow from plants to consumers, to a distributed bidirectional electricity flow system, poses new challenges such as the need of new operational strategies, models or simulation tools and infrastructure design (technological development and adaptation to a wider distributed grid). The interaction between distributed agents as smart houses or buildings, energy conversion technologies or electric vehicles (EV), and the electric grid has therefore been an issue that has prompted the interest of researchers, industry and policy makers. These interactions related to technical agents are supported by social/economic agents like prosumers, retailers, Distributed System Operators (DSO) or service companies, which are in fact crucial to drive the interactions at a technical level. Standardisation requirements and a better understanding of interoperability phenomena, especially the impacts that large scale trend integration of distributed agents may have, are subjects of interest for industry, utilities, regulation and policy making organisations.

The Smart-Grid Interoperability Lab at the Joint Research Centre (JRC) (U.S. Department of Energy's and the European Commission's respectively) develops industry-government cooperation focusing on the joint establishment of comparable EV standards and test procedures. One of the research goals of the lab is to study the interoperability between EVs and the corresponding charging infrastructure. Among others, the lab's research focus is on studying the interaction between the grid and other agents as well as identifying gaps in standards or technologies and proposing recommendations of solutions.

The electricity industry has recommended shifting over time to Mode 3 charging (IEC 61851) [1] as the preferred solution for all types of locations, making fast charging an important area to be addressed, especially its wide scale adoption. Mode 3 refers to slow or semi-quick, single-phase or three-phase options of charging. Mode 3 connectors according to IEC 61851 require a range of control and signal pins for both sides of the cable. The charging station socket will not work if no vehicle is present and has a pilot pin in the plug on the charger side which controls the circuit breaker. For compatibility, the 32 A plugs of IEC 61851 Mode 2 connectors may be used, while fast charging with higher currents up to 250 A requires specialized cables flagging the IEC 61851 charging mode. The communication wire between car electronics and charging station allows for integration into smart grid scenarios.

Topics for the analysis of EV charging impacts on distribution networks can be listed as voltage regulation, harmonic distortion levels, unbalances, additional losses and transformers loss of lifetime. Regarding power quality, a distributed system means a more horizontally structured grid hence, the impacts of harmonics become relevant to study in Points of common coupling (PCC). Battery chargers for Plug-in Electric Vehicles (PEVs) have high ratings and employ nonlinear switching devices which may result in significant harmonic voltage and currents injected into the distribution system. Fast charging suggested as the preferable way to attract end users and mitigate the PEV (Plug-in Electric vehicles) average autonomy, imply precisely these types of nonlinear loads.

Literature reports different findings regarding power quality impact from EVs. Some authors [2], [3], [4], [5] defend distribution networks can have limitations in EV charging support even for a relatively low EV penetration levels. Other studies [6][7][8][9][10][11], suggest that low PEV penetration levels, with normal charging rates, will have acceptable low harmonic levels and voltage variations, however fast charging rates could cause significant voltage harmonics and losses. Most of the studies tend to focus only on current harmonic, addressing as main concern the residential and normal chargers, as they are expected to have higher penetration. There is however, very limited number of studies which analyse both voltage and current harmonics focusing on fast charging specially performed in a cluster of chargers connected to the same feeder [12], [13]. Their high expected impact on energy demand, customer acceptability during the day, and expected usage during peak hours, makes these types of chargers/loads pertinent of study.

The findings of this research are relevant to the dimensioning and implementation of charging systems considering power quality issues. Within this context, this document intends to report the findings from the measurements performed in the laboratory, with the main goal of clarifying the following questions:

i) Investigate the Total harmonic distortion (THD) impact (voltage and current) caused by fast charging one single electric vehicle and standard limits compliance.
ii) How does the THD caused by fast charger/EV load vary along the charging cycle if at all?
iii) Does the THD and TDD caused by charging two EVs with the same fast charger decrease due to phase cancellation?

Considerable literature focuses on the distribution networks especially concerning residential networks [14][15], where the EV charging could bring severe addition of power electronic load and associated power quality issues. Studies compare results with European standard for public power supply is EN 50160 [16], which sets conditions for i) voltage magnitude variation, ii) voltage harmonics iii) inter-harmonic voltage, iv) voltage unbalance among others. All loads that are connected to the power network must provide so low effect on the network that it does not cause a violation of the power supply conditions stated in this standard. This means also that the EV chargers, once connected to a public network, must not influence the network operation to the extent that can cause deviation from the standard.

The requirements in terms of power quality specifically for the EV chargers are currently not standardised. In general, EV chargers have to fulfil requirements for loads that can be connected to electric power network described by electromagnetic compatibility IEC 61000 series standards. These standards set the emission levels, including the harmonic currents or power factor that a charger is allowed to have. The standards applied to the low-power EV chargers are IEC 61000-3-2 [17] and IEC 61000-3-4 [18], which set limits to the harmonic emissions generated by the charger. In [4] for different controlled battery charger, shows that there is a variety of topologies offering THD_I (current total harmonic distortion) well below 5% at load of 50…100% of rated power. The study shows that the harmonics levels remained lower than the limitations by applicable standards. Ranging between 90 V and 240 V, the study reports that with higher charger input voltage, the lower harmonics (below 13^{th}) are slightly higher than with low voltages, while for the lower main voltage the higher harmonics (above 15^{th}) present higher values.

Another study based on practical measurements of charging commercial EVs [8] presents a maximum THD_I of 17.3% for level III charger at the end of the charge, and maximum of 19.2% for Level I and II also at the end. This publication acknowledges that the TDD use would improve the conclusions regarding the distortion impact. Results from [9] case study in Portugal reports a THD_I of 11.6%, during the constant charging stage in a fast charging station when the actual operation is integrated in a commercial facility.

A typical distribution network has a large number of different non-linear loads connected to it. Authors in [19] defend that adding EV chargers from different manufacturers may result in a variety of different harmonic patterns. The diversity of the patterns may lead to notable harmonic cancellation. This effect occurs when harmonics with different phase angles provide a sum in the magnitude that is smaller than the individual harmonics magnitudes. It is however rather complicated to evaluate this effect. Authors in [10] studying low voltage nonlinear loads also suggest that cancellation is more probable as the number of consumers and appliances increase. It has also been indicated that harmonic cancellation is more expected at higher harmonic orders, which can then account for the relatively minor THD_I decrease. In most papers, it is rather common that only the harmonics amplitude levels are observed, as the utilities are required to keep the harmonics levels under a given limit. Authors in [20] however defend that if the diversity of chargers is not taken into account, the harmonic problems could be overestimated.

One of the first papers in this area was actually presented by [21] where multiple different EV chargers in the network have been observed. There are 5 different rather simple charger topologies described, assigned for samples of EVs. Several probabilistic parameters are included such as distribution of charging times and SOC. Monte Carlo simulation method with sample size of 100 is used for the analysis of the complicated system. It is reported, that 10% smaller harmonic current magnitudes were observed compared to the simple summing of magnitudes.

A more recent publication [22] applies a methodology which accounts for diversity of SOC and initial charging moments in California. The results indicate that accounting for variation in start-time and SOC in the analysis leads to reduced estimates of harmonic current injection. Authors argue that traditional methods do not account for these variations. Researchers show that from the point of view of the substation transformer, the impact of EV's is mainly one of power and energy, rather than harmonics. Analysis with real and imaginary components for each harmonic has been described in [7]. The paper analyses 20 kWh charges and reports a THD_I over 40% at connection point. The 11 kV medium-voltage network has been simulated with 36 chargers, each at power level of 8.2 kVA, which makes it difficult to witness the total cancellation effect.

There is still a lack of overview on the matter regarding harmonic cancellation. Nonlinear loads have their own specific harmonic patterns that can contribute to the harmonic cancellation. A concern when different loads are considered is that such different loads/vehicles have different SOC connected to the system. This means that if current variation during the charging cycle exists, it may be expected small frequency variations and with it different phase angles for the some harmonic from other chargers. There is a lack of studies focusing on fast chargers clustering and the impacts on both THD_I and THD_V (voltage total harmonic distortion) referring specifically to fast charging. These are of high importance to study due to the load high individual rated power and its likelihood of working in large groups during peak hours.

It is of high importance to study the phase angles in order to understand how the amplitude of the harmonics measured will sum when considered part of a cluster. This would mean that to comply with the standards limitations, upper bound on the maximum number of EV should be taken in consideration if the robustness of the system in terms of short circuit current (I_{SC}) was to remain the same.

This document reports the field work and measurements from an EFACEC Q45 fast charger [23] using a VW E-UP in order to understand the amplitude, SOC and phase angle variation, to find out if random, similar or preferential angles can be expected from the device.

2. Theoretical background

Harmonic distortion is a deviation of the current or voltage waveform from a perfect sinusoidal shape. In the case of nonlinear loads, such as EV charge controllers, current distortion is very common due to the need of power electronics switches to convert power from an AC to a DC form. Introduction of these currents into the distribution system can distort the utility supply voltage and overload expensive electrical distribution equipment. In order to prevent harmonics from negatively affecting the utility supply, standards such as the IEC 61000-3-12[24]/2-4[25] or the IEEE Standard 519-1992 [26], were established with the goal of developing, recommended practices and requirements for harmonic control in electrical power systems'. These wide adopted standards, by the industry and research community, describe the problems that unmitigated harmonic current distortion may cause within electrical systems as well as the degree to which harmonics can be tolerated by a given system. Utilities are obliged to provide power quality whose limits among others depend on the level of voltage connection. End users on the other hand, are responsible for not degrading the voltage of the utility by drawing significant nonlinear or distorted currents. Utility and user's relationship is hence drawn by the following drivers:

• Utilities are responsible for providing "clean" Power;
• Customer is responsible for not causing excessive current harmonics;
• Utility can only be fairly judged if customer is within its current limits at PCC.

It is therefore evident that the power quality, specifically harmonic impact in PCC (Points of common coupling) is a subject of interest to both parties. The Point of Common Coupling (PCC) with the consumer/utility interface is the closest point on the utility side of the customer's service where another utility customer is or could be supplied. The PCC is hence many times considered to be on a medium voltage level for most of industrial application, however for the rest of low voltage consumers it may make sense to consider it on a low voltage level.

Some authors prefer to define the PCC (or multiple PCCs) at a point (or points) internal to the customer's system. This implies that harmonic limits must be met internally, in the customer's system which is not the intent of the standard. Many industrial users own large internal electricity facilities, and may force manufacturers of nonlinear loads to follow the limits for a single load which can result in significant costs for end users. The goal of applying the harmonic limits specified in the standards is to prevent one customer from causing harmonic distortions to another customer or the utility. If a consumer's device causes high harmonics within its own system, this is only harmful for the customer's device without, necessarily violating the standards. In the case where one user installation has multiple feeds from the utility, the use of multiple PCCs would be required, since different impact may be read in the different feeders. The PCC is the only point where one must meet the standards limits, in case the standard is incorporated into the contract or applicable rate. It is therefore important to bear in mind the following:

- PCC is where harmonic limits are assessed;
- Where intended to prevent one customer from harming others;
- Not intended to be applied within a user's system;
- Not always practical or necessary to measure the true PCC for practical reasons;

2.1. Harmonics

Harmonic topic in theoretical terms is a well-covered subject. In practical terms however, it is difficult to assess the phase angles from each harmonic and therefore to make valid assumptions regarding the way they add up when multiple devices interact. Most of the times, probabilistic approaches are made [20][27], and often studies will only treat the vector summation with high uncertainty or worst case scenarios are taken in consideration [28]. Literature's results and conclusion often differ as follows:

- The summation of two harmonic vectors at same frequency is only certain if their amplitudes and phase angles are well known.
- At most cases, only the harmonic amplitudes are given or recorded, while the phase angles are usually unknown.

As exemplified in Figure 1, consider two loads J1 and J2 connected to a grid with the impedance Z_h:

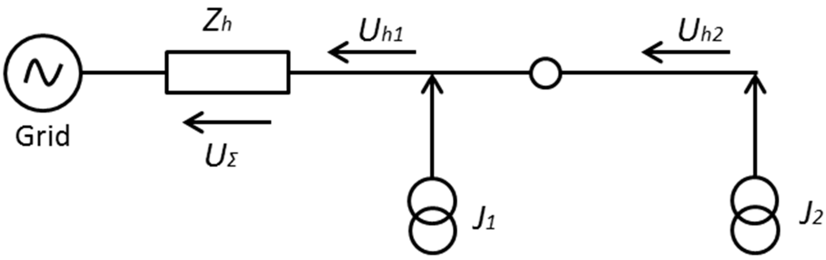

Figure 1 – Simplification example of two loads connection to the same grid feeder

The vectors U in Figure 1, with harmonic voltage order h, will sum ($U_{h\Sigma}$) according to Equation (1), where θ is the phase angle related to the fundamental.

$$U_{h\Sigma} = \sqrt{U_{h1}^2 + U_{h2}^2 + 2U_{h1}U_{h2}\cos(\theta_{h2} - \theta_{h1})} \quad (1)$$

However if the angles are unknown and if no probability function exists for θ, one can use the properties of a uniform distribution to deduce the probability of a conservative summation by upper and lower deviation phase angles establishing as shown in Equation (2) the limit between 0 and π where,

$$f(\theta) = {}^{1}/_{\pi}\ ,\ \theta \in [0, \pi] \quad (2)$$

Equation (3) shows the expected mean value obtained by:

$$E(\theta) = \int_0^{\pi} \theta f(\theta)\, d\theta = \frac{\pi}{2} \quad (3)$$

And the corresponding standard deviation in Equation (4) is:

$$\sigma(\theta) = \sqrt{\int_0^{\pi} \theta^2 f(\theta)\, d\theta - [E(\theta)]^2} = \frac{\pi}{2\sqrt{3}} \quad (4)$$

This can give the upper and lower phase angles estimations as follows in Equation (5) and (6):

$$\theta_{upper} = E(\theta) + \sigma(\theta) = \frac{\pi}{2}\left(1 + \frac{1}{\sqrt{3}}\right) \rightarrow 141.96°, \quad \text{p=78.86\%} \tag{5}$$

$$\theta_{lower} = E(\theta) + \sigma(\theta) = \frac{\pi}{2}\left(1 + \frac{1}{\sqrt{3}}\right) \rightarrow 38.04°, \quad \text{p=21.13\%} \tag{6}$$

In case the statistical distribution or exact angles are known, they will add up in case their difference is below 90 degrees (add perfectly if 0°) or subtract if below (cancel each other if 180°). Equation (1) will only provide the resulting amplitude of the angle, however to calculate the summation of various vectors, the resulting angle of each sum is also required and can be calculated analytically by decomposition of the X and Y components.

Consider two vectors A and B in Equation (7)-(8) and (9)-(10) where A_1 and A_2 are the vector's amplitude and θ_1 and θ_2 are the corresponding angles, we have:

$$A_x = A_1 \cos\theta_1 \tag{7}$$
$$A_y = A_1 \sin\theta_1 \tag{8}$$

and,

$$B_x = A_2 \cos\theta_2 \tag{9}$$
$$B_y = A_2 \sin\theta_2 \tag{10}$$

After obtaining the R_X (by adding the X and Y components), the resulting amplitude (R) in Equation (11) and angle (θ_R) in Equation (12) are given by:

$$R = \sqrt{(R_X^2 + R_Y^2} \tag{11}$$
$$\theta_R = \tan^{-1}(\frac{R_Y}{R_X}) \tag{12}$$

Another way to view addition is that two vectors with coordinates [A1 cos(ωt + θ1), A1 sin(ωt + θ1)] and [A2 cos(ωt + θ2), A2 sin(ωt + θ2)] are added to produce a resultant vector with coordinates [A3 cos(ωt + θ3), A3 sin(ωt + θ3)].

2.2. Standards

Several standards have been developed aiming at improving the power quality and specifically the harmonic content issue. They have been applied depending on the nature of the load and its installation level. Standards can be categorized in three groups:

i) Standards related to power quality in distribution networks:

- The IEEE-519[26] is a joint approach for customers/utilities to limit nonlinear load harmonics
- The EN-50160[16] focuses on voltage characteristics of public electricity distribution grids
- The IEC-61000-6[29] is mostly focused on harmonic limits for power quality (planning level)

ii) Standards related to devices and harmonic sources:

- The IEC-61000-3-2[17] and IEC-61000-3-12[24] advocate harmonic limitations for low-voltage equipment

iii) Standards related to distribution network equipment installation and operation

- The IEEE-1547[30] defines the requirements for distributed resource (DR) interconnections including harmonic distortions in DR applications.
- The IEC-61000-2-4 [25] defines harmonic limits for equipment immunity in LV and MV installations.

2.2.1. Standard IEEE 519, IEC 61000 and EN 50160

IEEE 519-1992 and IEC 61000-3-12/2-4 are the respectively American and International standards which apply to the case under study. Both discuss the impacts that harmonic distortion can have on distribution assets, particularly transformers, power cables, capacitors, metering, relaying and switch gear. Harmonic distortion also affects nearby loads, particularly power electronics devices and motors. It proposes limits both for voltage and current distortions and even limits for individual frequencies. The IEEE 519, presents the voltage limits, still making a clear distinction between THD_I and TDD needs.

EN 50160 gives the main voltage parameters and their permissible deviation ranges at the customer's point of common coupling in public low voltage and medium voltage electricity distribution systems. However the load current is not relevant to EN 50160. Regarding the actual current harmonic limits the European standards are akin to IEC, hence only the latter will be referred to onwards.

Table 1 shows the Voltage Total Harmonic Distortion limits for different voltage levels:

Table 1 – Voltage Distortion Limits set in IEEE 519-1992

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3	5
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user

Similarly Table 2 shows the limits for the TDD and individual harmonics according to each voltage level. It is important to distinguish between THD and TDD when using this table.

Table 2 – Maximum Harmonic Current Distortion in Percent of I_L set in IEEE 519-1992

Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	11≤ h <17	17≤ h <23	23≤ h <35	35≤ h	TDD
< 20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L (I_L - Maximum demand load current and I_{SC} – Short Circuit current). TDD – Total Demand distortion, harmonic current distortion in % of maximum demand load current (15 or 30 min.). Even harmonics are limited to 25% of the odd harmonic limits above. Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed.

Table 3 - Maximum Harmonic Current Distortion in Percent of I_L set in IEC 61000-3-12

Minimum RSCE	Admissible individual harmonic current I_h/I_{ref} (%)				Admissible harmonic parameters (%)	
	I5	I7	I11	I13	THC/$_{Iref}$	PWHC/I_{ref}
33	10.7	7.2	3.1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
≥350	40	25	15	10	48	46

The relative values of even harmonics up to order 12 shall not exceed 16/h%. Even harmonics above order 12 are taken into account in THC and PWHC in the same way as odd order harmonics. Linear interpolation between successive R_{SCE} values is permitted

R_{SCE} - Short-circuit ratio; I_h-Harmonic current component; I_{ref} -Reference current; THC-Total Harmonic Current; PWHC-Partial Weighted Harmonic Current

Table 4 - Voltage Distortion Limits set in IEC 61000 2-4

Harmonic order n (Non multiples of 3)	Class 1 µn [%]	Class 2 µn [%]	Class 3 µn [%]
5	3	6	8
7	3	5	7
11	3	3.5	5
13	3	3	4.5
17	2	2	4

Class 1 Compatibility level lower than public (laboratory instrumentation, some protection equipment, etc.). Class 2 Compatibility level equal to public (any equipment designed for supply from public networks). Class 3 Compatibility level higher than public (equipment in the presence of welding machines, rapidly varying loads, large converters, etc.)

THD_V	5%	8%	10%

I_{SC}/I_L ratio shows relative size of the load compared to the utility system. Power systems in a given point (under linearity hypothesis) can be transformed into a Thevenin equivalent with the related impedance. The short circuit, which may also be expressed in short-circuit power (SCP) in MVA, at that point "quantifies" the equivalent impedance of the network. If it is high (low SCP) the network is "weak" and the voltage is affected by the (harmonic) currents; if it is high (infinite), the impedance is zero and the network is strong and the voltage is not affected.

It is hence necessary to calculate or to measure the short circuit current (I_{SC}) at the PCC where the measurements are intended. TDD is very similar to THD, except for the denominator as shown in Equations (7) and (8). In TDD, harmonics are expressed as % of I_L (maximum demand load current) whereas THD present harmonic content expressed as % of I_1 (fundamental current). For the I_L it is advised to consider the maximum averaged current of at least a 15-30 minute interval of the last 6 months for a given costumer.

$$THD_I = \frac{\sqrt{I_2^2+I_3^2+I_4^2+I_5^2+\cdots}}{I_1} \tag{7}$$

$$TDD = \frac{\sqrt{I_2^2+I_3^2+I_4^2+I_5^2+\cdots}}{I_L} \tag{8}$$

Standard IEEE 519 suggestion is to try to ensure all harmonic loads and all linear loads run during the measurements. This will provide a closer match of THD and TDD, and so easier to assess limits. In practical terms the THD is measured first and then a comparison is made to the limits, if there is a problem then the TDD is calculated. It is rarely needed to convert to the TDD and % of I_L, which is why the THD concept is much better known. With such approach one can know the following:

- Harmonics meters measure THD and % of I_1
- If THD and % of I_1 measurements meet limits, then TDD and % of I_L values will also meet limits;
- Only convert to TDD and % of I_L when necessary;

It is important to distinguish between the two concepts in order to prevent users from being unfairly penalized during periods of light load as harmonics could appear higher as a percent of a smaller I_1 value.

2.3. System Imbalance

Nonlinear loads create imbalances in three-phase systems. When such phenomena occur, the fundamental current and voltage in one phase differs from the others. This produces what is referred to as zero-sequence components. These zero-sequence components are comprised of the non-even multiples of triple harmonics. Examples of these are the 3rd, 9th, and 15th harmonics. Zero-sequence components are troublesome because they add up in the neutral line of a star (Yn) configured system or circulate in the case of a delta (Δ) wired system. When these zero-sequence currents superpose in the neutral line, they can cause excessive currents and can lead to conductor heating [31] or even unwanted intervention of protective over-current relays during normal operation, causing wide interruptions and compromising service continuity of supply. The unbalance in the system will be verified during the charging cycle, which in case it is in fact a balanced system can facilitate the analysis since addressing only one phase will be the image of the others.

3. Test Design

Four sets of measurements were performed of a full electric vehicle using a commercial combo fast charger. As a measurement device the Fluke 437 Series II [32], 400Hz Power Quality and Energy Analyser was used, set with 0.25s time step data acquisition. The harmonics were registered until 2500 Hz. The resolution and accuracy of the THD for both voltage and current is 0.1% and ±2.5% respectively, whereas for the phase angles is 1° with an accuracy of ±n x 1° (where n is the harmonic order). The EFACEC model Q45 fast chargers [23] was connected to a 63 A outlet, 230V, 50Hz at one end and at the other, with the chargers manufacturer's cable, to a full electric vehicle VW model E-Up, with an 18.7 kWh battery pack.

The vehicle was discharged by random driving cycles and a different measure was performed on different days. One can consider the temperature of the battery similar in all measurements. The Laboratory temperature was approximately 25 C°. All loads inside the car were disconnected (air conditioning, radio, lights). The 4 sets of measurements were performed from low and different states of charge 8%, 7%, 5%, 10% respectively to 100% SOC which lasted a maximum of 32.5 minutes.

Before starting the measurements, in addition to phase sequence verification, an initial conditions verification procedure was performed. This was intended to mitigate the fact that not all measurements were recorded at the same time, and that no voltage control source was used. A set of three files were recorded per measurement: i) No load, ii) only with the charger connected iii) with load. This was intended to verify the following conditions:

- Frequency fluctuation;
- Voltage Fluctuation;
- THD_V present with no load;
- THD_V only with the fast charger connected;

The upstream grid representation is shown in Figure 2, as well as the point where the measures were taken, i.e. Point of common coupling.

The PCC in theoretical terms will often be at the medium voltage level which is to say the primary of the distribution transformer serving the users, irrespective of transformer ownership or the location of the metering system. In practical terms however, it is often more secure or accessible to perform such measurements on the transformer secondary, as is the case presented in this analysis. To calculate the resulting voltage distortion on the transformer primary, system modelling would be required, whereas the current percentages would transform straight through.

Measurements on the transformer secondary are most of the times sufficient to determine whether there is a harmonics problem, so it is not necessary to use the precise PCC definition. If there is an identified abnormal phenomena and a disagreement between a utility and a customer occur about harmonic standards levels compliance, the higher level of PCC will then be considered and the values recalculated. In the present study we consider that a distinction of consumers would be done at the PCC point shown in Figure 2. An Impmeter 2 instrument was used to record the I_{SC} at the PCC and with the identified I_L during each measurement the standard limits were identified.

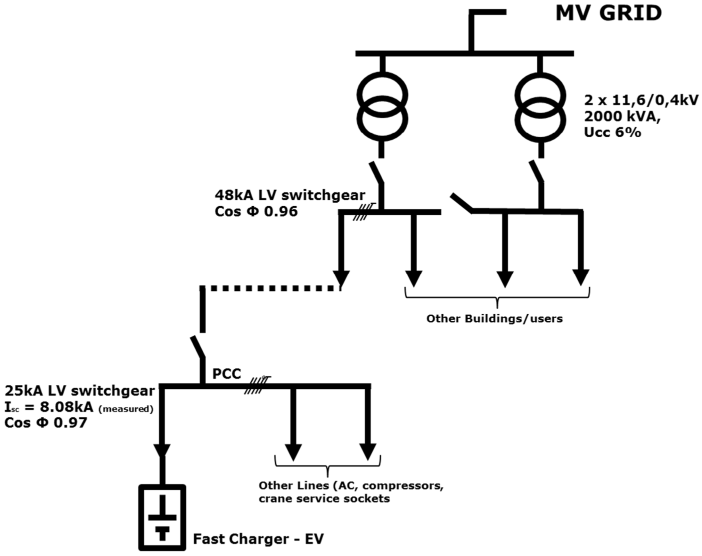

Figure 2 – Simplified Single Line Diagram of upstream electricity grid, from PCC until MV level.

To accomplish the first and second goals of this research, after the measurements were performed, PowerLog 4.2 software [32] was used to import and verify the reading. The data from the four sets of measurements were then exported to spreadsheets. Values of THD were observed and compared with TDD, the ARMS current during charging cycle was registered and all shown in the result and discussion chapter.

The individual harmonics were treated in order to present the amplitude in Ampere unit since the device reported them as a relative value to the fundamental. The product of this value by the ARMS current of each reading divided by 100% provided the intended result. From the absolute and relative values a comparison with the standard limits was possible. These values were also important to obtain in order to simulate the THD and TDD with one and two electric vehicles working together. Since the system is balanced, the analysis was only performed in one phase.

To pursue the third challenge of this research, apart from the amplitudes of the harmonics the phase angles were also analysed. Using the Crystal-ball excel add-in, the time series of each angle and phase were submitted to a curve fit calculator (based on Anderson–Darling statistical test). The phase angles from each frequency were analysed and their corresponding statistical distributions were analysed regarding to their range differences. After this analysis, a simple simulation was carried out with the goal of obtaining the corresponding TDD resultant from charging one vehicle or two vehicles in the same feeder. As inputs for the simulation, the complete data set of approximately 32.5 minutes was taken in consideration from two different load measurements for one single phase. Using Crystal-ball, both absolute values of amplitudes and phase angles statistical distributions were used to apply Equation (1) to the harmonics. By using Equation (8) the two TDD were found and compared.

4. Results and Discussion

4.1. Results from Measurements

Measurements were taken for approximately 32.5 minutes with 0.25 s time steps. This generated approximately 8000 records for each variable, for practical reasons a simplification of 7 events during the charging cycle is given in Tables A1-A4 presented in the annex, for each measurement respectively. All the even harmonics until the 25th are shown, as well as the THD_I of each phase in the corresponding minute.

In all measurements one can verify high predominance of the 11th, 13th, 5th and 3rd harmonics. Furthermore, higher variability in the phase angles is observable in the 3rd and 9th harmonic (Figures A1-A6), whereas the other even harmonics present a relative narrow angle range. The THD_I tends to increase at the end of the charging cycle which can be explained by the decrease of the current at the end of the cycle, as shown in Figure 3. This can be misleading if only the THD_I is considered, since it takes into consideration the fundamental current as reference. The THD_I can reach as high as 40% in the 4th measurement shown in Table A6, however the current which it refers to is below 10 A instead of 67.5 A during most of the charging, where the TDH_I is approximately 11%-12%. For this reason the analysis of the TDD which considers the maximum current instead of the fundamental is more elucidative of what is under study.

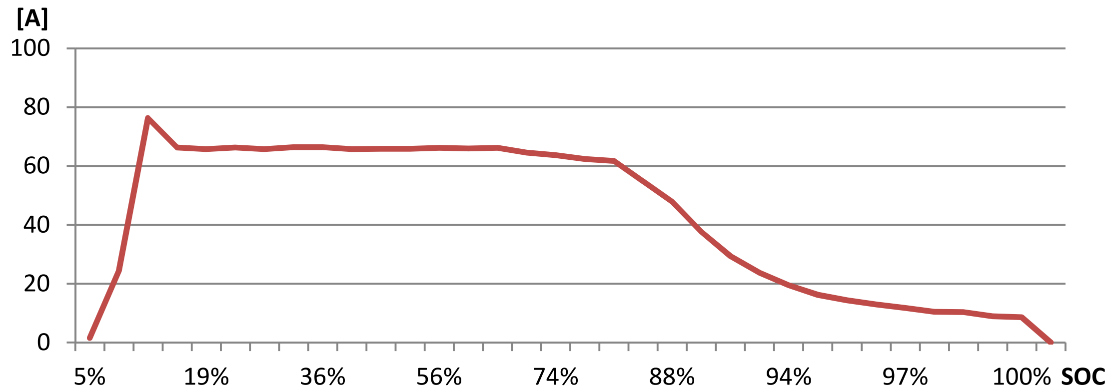

Figure 3– Current behaviour during a charging cycle (18.7 kWh load) (L_1)

From Figure 3 and 4 it can be observed three distinct stages: First during the first 2-3 minutes of charging with very high TDD_I peaking to more than 50% while TDD starts low, a second stage with a constant behaviour where TDD and THD present very close values of 11.5% to 12.5%. A third stage can be distinguished during the last 15 minutes corresponding to 77% to 100% SOC where the current starts decreasing, making the THD reach a maximum of 36% and TDD drop to 3%.

The graphics in Figure 3 and 4 correspond to 7890 events of 0.25s which corresponds to 32.87 minutes of charge. It should also be highlighted in Figure 3 that the last 15% to 20% SOC lasts 1/3 of the time (12 minutes), where it only takes the other 2/3 of the time (20 minutes) to reach 80% State of charge.

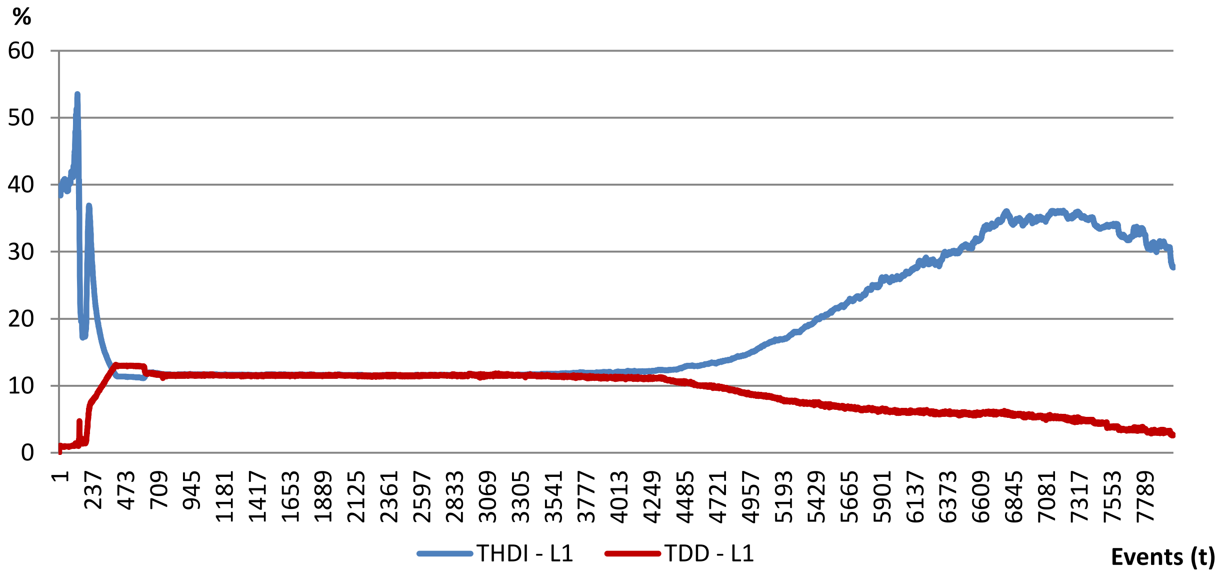

Figure 4 – THD_I and TDD during the charging cycle (18.7 kWh load) – L_1

Values of both TDD and THD_I are coherent with others presented in the literature [8], [9]. For TDD calculations it is suggested that the average current for the maximum demand over the previous 12 months should be taken in to consideration. However this value was not possible to assess and so TDD calculations were based on the maximum current of 67.5 A demand during the charging cycle (even though a peak of 76.7 A was recorded, it only lasted 40 seconds and therefore was neglected). Maximum value of TDD was 13.12% and for the THD_I was 51.93%. The readings enhance the need of separating the analysis using the fundamental and the maximum demand current. Regarding the $THD_{V,}$ Figure 5 presents the complete behaviour during the charging cycle for phase L1. The time evolution is coherent with the current one shown in Figure 3.

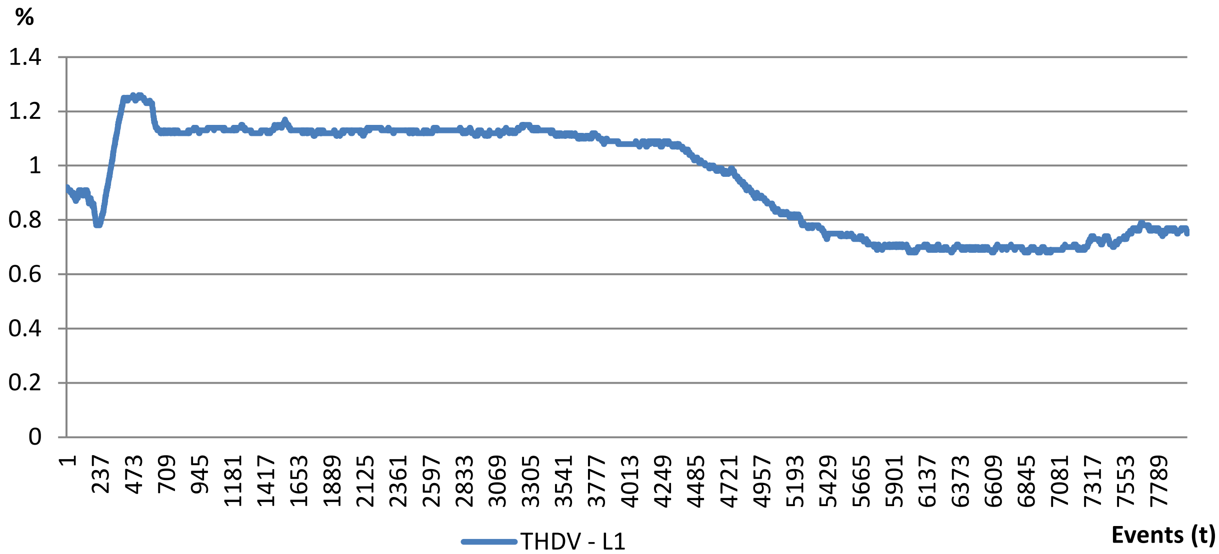

Figure 5 – THD_V during a complete charging cycle (18.7 kWh load) – L_1

The voltage starts decreasing at approximately 75% SOC, which also happens with the current, meaning that this stage has a lower power being fed into the battery. This has to do with the battery charging curve characteristic, which seems normal with such a technology. The lower power in this stage is the reason why the last 12 minutes only charge about 15% of the charge. The Voltage THD in the initial stage reaches 1.26%

distortion and it stabilises 1.16% during the constant stage, dropping to 0.7% at the final stage which are all below the 5% limit [26]. The harmonic histogram for both voltage and current can be seen in Figure 6. Even harmonics for low frequency were excluded due to their low contribution and only harmonics until the 25th are shown, since above this their values are negligible. One can verify that the odd harmonics are the most significant especially the 11th, 13th, 5th and 3rd. Their lower or higher relative values as shown in the picture do not reveal the total importance of their individual analysis, since their limits set by the standards become lower as the frequency increases. For this reason all odd harmonics until the 25th were analysed.

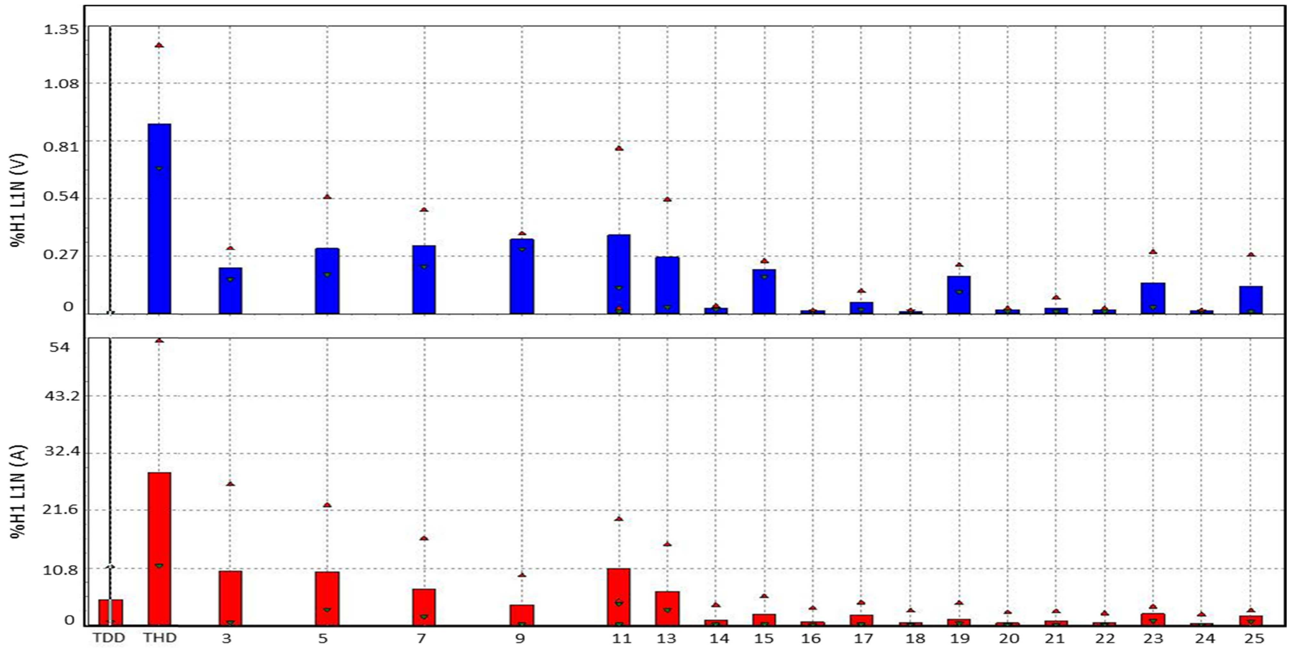

Figure 6 – Harmonic histogram from 18.7 kWh load

For the analysis of the phase angle range, each odd harmonic frequency was compared with the other measurements by phase. An example is given in Figure 7 for the 9th harmonic and phase 1, which even though it is not one of the highest impacting the distortion, from the data analysed is the one which presents the highest variations in terms of angle range (at this harmonic order the accuracy is +/- 9 degrees). The range however, is not uniform and actually tends to have a higher density (in terms of event number) around an average. This means that it can be drawn a statistical distribution from all the harmonics and ranges. Other harmonic frequencies are shown in Figures A1- A6 in the Annex which also show preferential range angles.

Comparing the statistical distributions between the 4 measurements of all harmonics, will provide the probability of two angles being within a range, i.e. if their amplitudes will tend to sum or subtract.

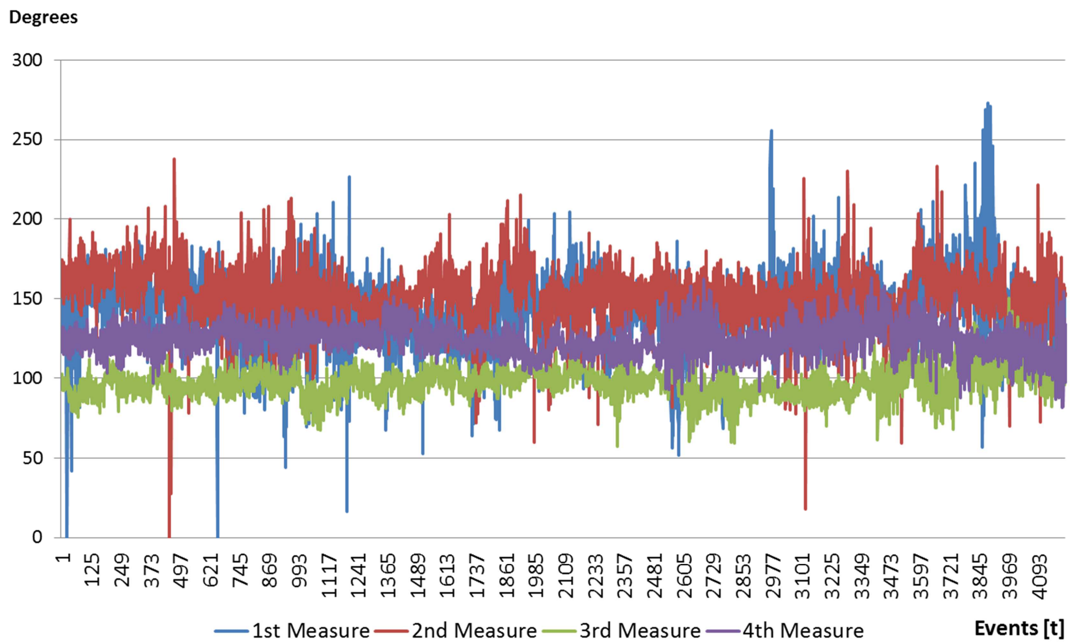

Figure 7 – 9th Harmonic phase angle range from the 4 measurements for L_1.

Computing all events in Crystal-ball software, a distribution can be drawn with the corresponding mean value and standard deviation. This was performed for all the significant harmonics (even harmonics until the 25th). Figure 8 shows the results the 4 measurements when analysing the 9th harmonic variation shown in Figure 7. In this example the best fit distribution for the first and third measurements of the 9th harmonic correspond to a Logistic Distribution. Likewise the second and fourth measurements correspond to a maximum Extreme Distribution.

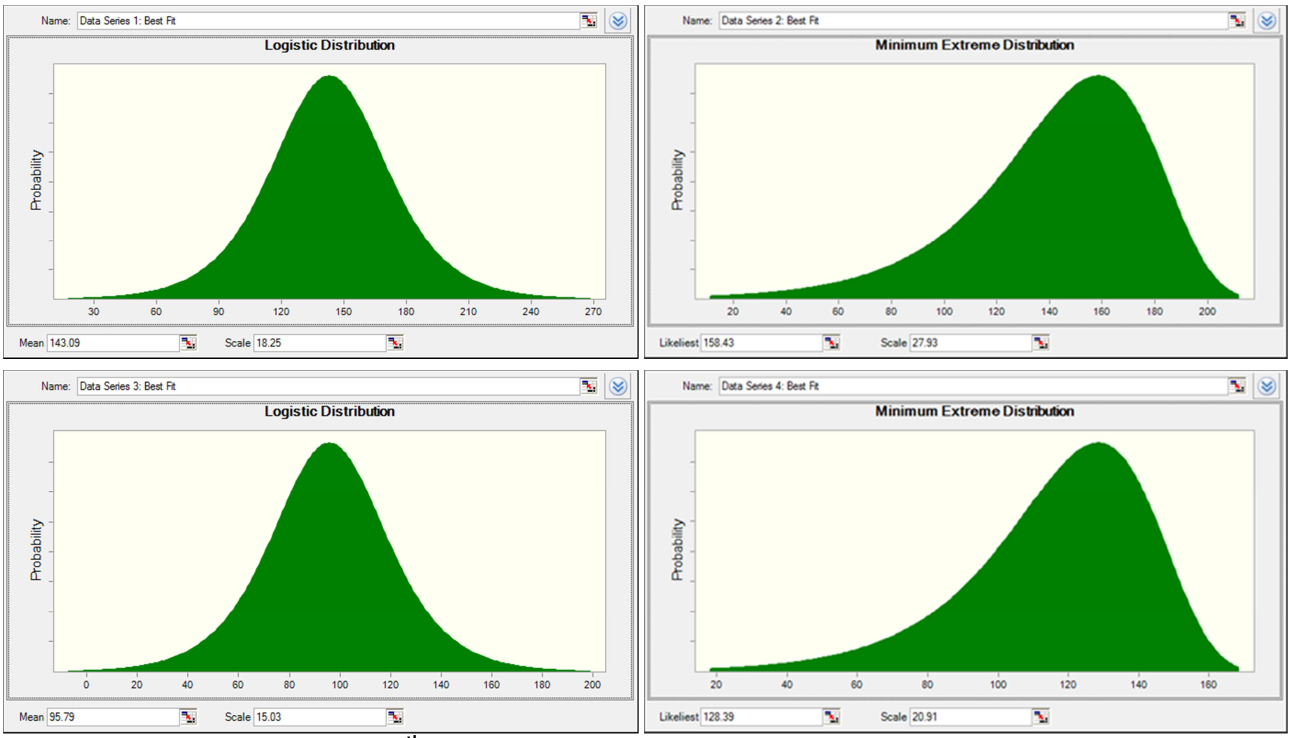

Figure 8 – Example of the 9th harmonic phase angles range statistical distributions for the 4 measurements.

As can be observed from Figure 8, even in this case, where higher angle variability is seen, the mean values from their common referential (the fundamental) vary between 95° and 158° and from each other their difference will be below 90°. This means it will allow an amplitude summation most of the time.

4.2. Comparison with the standard limits

As it was verified that the current and the THD_I changed during the charging cycle, for a fairest analysis the TDD should be used, hence for the sake of the research analysis a higher focus will be given to the IEEE 519 standard, but in all applicable to IEC standards. Apart from the TDD limit values presented in the standard, also individual harmonics must comply with the limits. From the harmonic histogram in Figure 6, one can verify that some harmonics such as the 11^{th} could be out of the limits set by both standards IEEE 519 and IEC 61000-3-12/2-4. To analyse the limit compliance, one must first identify the limits to consider in Tables 1-4. The I_{SC} value was measured in the General Low Voltage Main Cabinet, which is the actual PCC under analysis. Values recorder ranged from 8080 A to 8480 A. For the identification of the system's corresponding row limits of the standards, the I_{SC}/I_L was calculated considering the most unfavourable scenario:

I_{SC} = 8.08 kA; I_L = 67,5 A → Ratio = 119.7

According to the Table 2 and 3 the TDD and THD limits are 15% and 16% respectively with the corresponding individual harmonic ones. Using the first measurement set as an example and using Crystal-ball, the assumptions for the harmonics amplitudes were made from the total charging cycle data sets. We obtained the corresponding forecasts regarding the individual impact of the harmonics, shown here only for 11^{th}, 13^{th}, 23^{rd} and 25^{th} in Figure 9. Is it possible that those harmonics may be in violation of the IEEE 519 and IEC 61000 3-12.

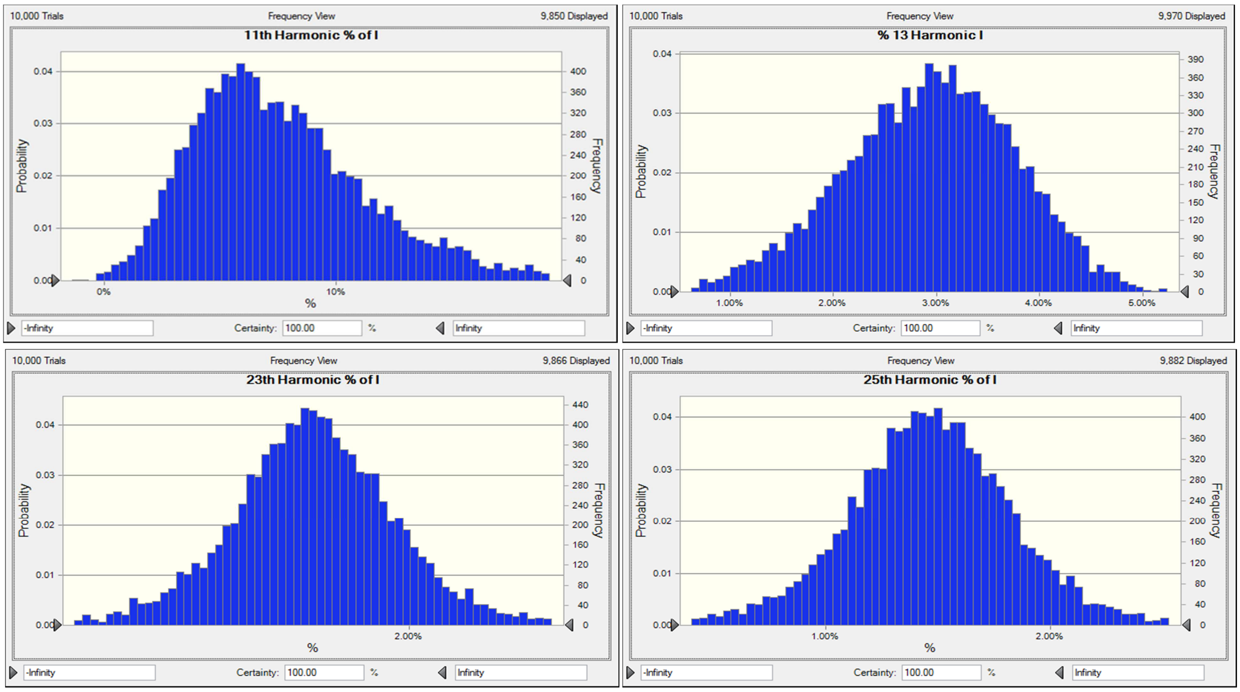

Figure 9 - Forecast of individual 11^{th}, 13^{th}, 23^{rd} and 25^{th} harmonics distortion.

Figure 9 shows that the limits of 5.5% from Table 2 or 5% and 3% from Table 3 are broken by the 11th and 13th, and even though less probable the 23rd and 25th may break the limit of 2% as well. As seen in Figure 4 TDD complies with the standard, but stays above 12% most of the charging cycle. It is important to stand out that the ration I_{SC}/I_L was close to be under 100. This would cause the limits of the TDD be 12% and in this case the charger would fail to meet these requirements as well. Regarding the THD_V, Figure 5 shows the voltage distortion within the limit of 5%, hence complying with the standard.

4.3. Simulating Two Electric Vehicles

To simulate two vehicles connected to the same feeder (both working at 67.5 ARMS), two sets of measurements (1 and 2) were considered. All odd harmonics until 25th and corresponding data from a complete charging cycle were considered in Crystal-ball as assumptions. Amplitudes and angle ranges were inputted as the best fit statistical distribution and ran for 10000 trials. All other harmonics, not analysed individually, were considered and have a fix amplitude of 6.1 A (to reach the measured real TDD of 12%) and that their angles would add as well. The TDD was forecasted for 1 and 2 vehicles and the results are shown in Figure 10.

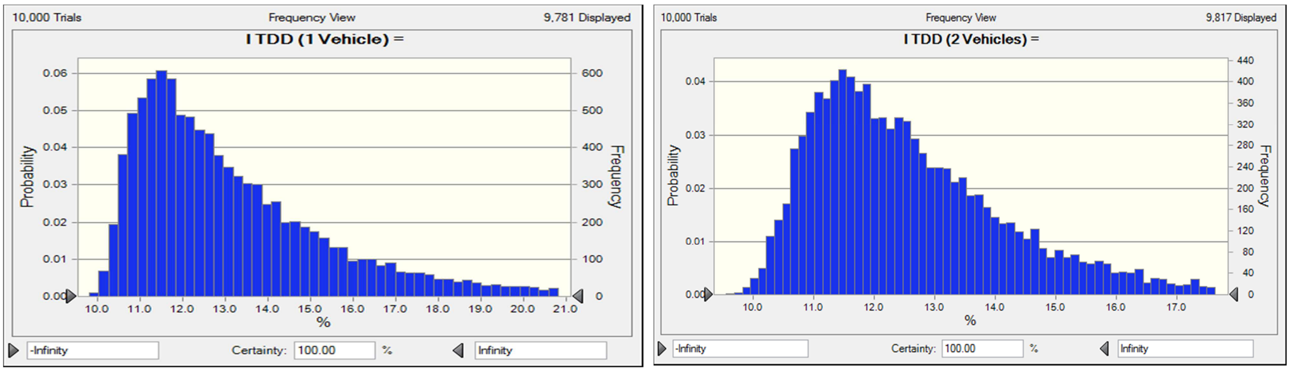

Figure 10 – TDD for 1 and 2 Electric Vehicle Simulation

Figure 10 shows that the simulation results with one and two vehicles will report very close values with a mean of 12% for the TDD. With two vehicles as expected the mean may be slightly inferior (11.7%) since the amplitudes do no add perfectly. Furthermore the standard deviation seems to have decreased when two vehicles are considered.

This means that, if the number of vehicles increases, the TDD will tend to be the same or to have a slightly decrease with this charger. Once again, this happens because preferential phase angles will make the amplitudes on average to add ($\Delta\theta<90$) but not perfectly (0 degrees). Furthermore as the current I_L also increases linearly with the EV number, the distortion remains the same. However if the I_{SC} is maintained this will eventually cause the break of the limits set on the IEEE-519 standard as seen in Figure 9 and 4. This means that more vehicles can be connected without increasing the harmonic impact. However it also means that if more vehicles are connected the I_L will increase and the ratio of I_{SC}/I_L decrease causing the harmonic limits to be broken eventually (if infrastructure is unchanged). It is extremely advisable that sufficiently high short-circuit power should be available at the interconnection point.

4.4. Other power quality issues observed

In addition to harmonic distortion, several other Power Quality (PQ) issues during the measurements were observed. This includes phantom loading and load imbalance (resulting in current in neutral lines).

4.4.1. Phantom Loading

An anomaly that was originally noticed after the first data collection phase was the consumption of power by the charging station even when there were no EVs connected to that station. It can be attributed a minor amount of phantom loading to the digital circuitry, LCD screens and indicator lights featured in most of the charging stations. These ancillary circuits consume a low level of power at all times, irrespective of whether an EV is charging at the station or not. It can be attributed a second type of phantom loading to the DC quick charger internal circuit (capacitors charging, internal filter, switching devices). In any case the power registered was very low. Figure 11 shows the current RMS in L_1 of one measurement during 5 minutes.

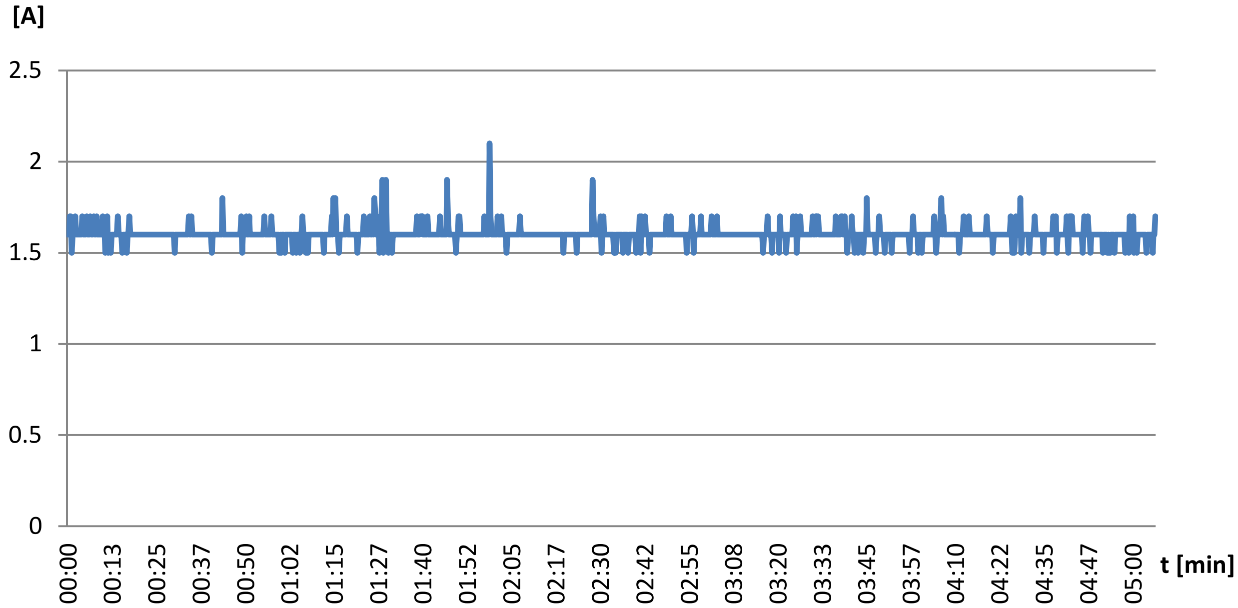

Figure 11 – Current reading with the fast charger connected and no vehicle load – L_1

4.4.2. Load Imbalance

Generally, systems are designed so that the loads are balanced across the three phases. By balancing the loads, the current in each of the three branches is roughly the same and the resulting terminal voltages are also roughly the same. Unbalanced loading can result in currents within the neutral line. Since neutral lines tend to be undersized compared to the hot lines these neutral currents can lead to excessive heating in extreme cases. Load imbalance also leads to voltage imbalance, which can be problematic for three-phase loads expecting equal phase voltages.

Imbalance in a three-phase system is defined as the ratio of the magnitude of the negative sequence component to the magnitude of the positive sequence component, expressed as a percentage. The voltage or current imbalance in the system was found to never exceed 1% at any given time as can be seen in Figure 12, showing currents only, for a complete charging cycle (phases maintain a 120 ° distance).

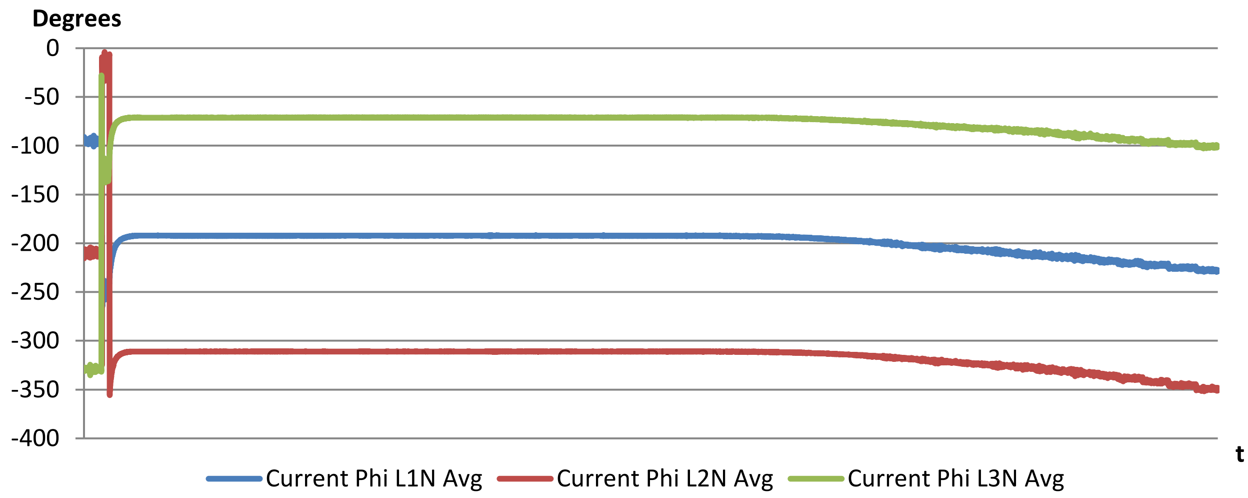

Figure 12 – Current angles from each of the three phases

4.5. Measurements with 24 kWh battery

In order to analyse if the harmonics preferential angles behaviour depended on the load and if the harmonic distortion was maintained, two measurements (7% and 19% SOC to 100% SOC) were performed in the same conditions, however using a VW E-Golf 24 kWh connected to the same fast charger. Figure 13 shows the THD_I and TDD for the 2^{nd} measurement (19% SOC).

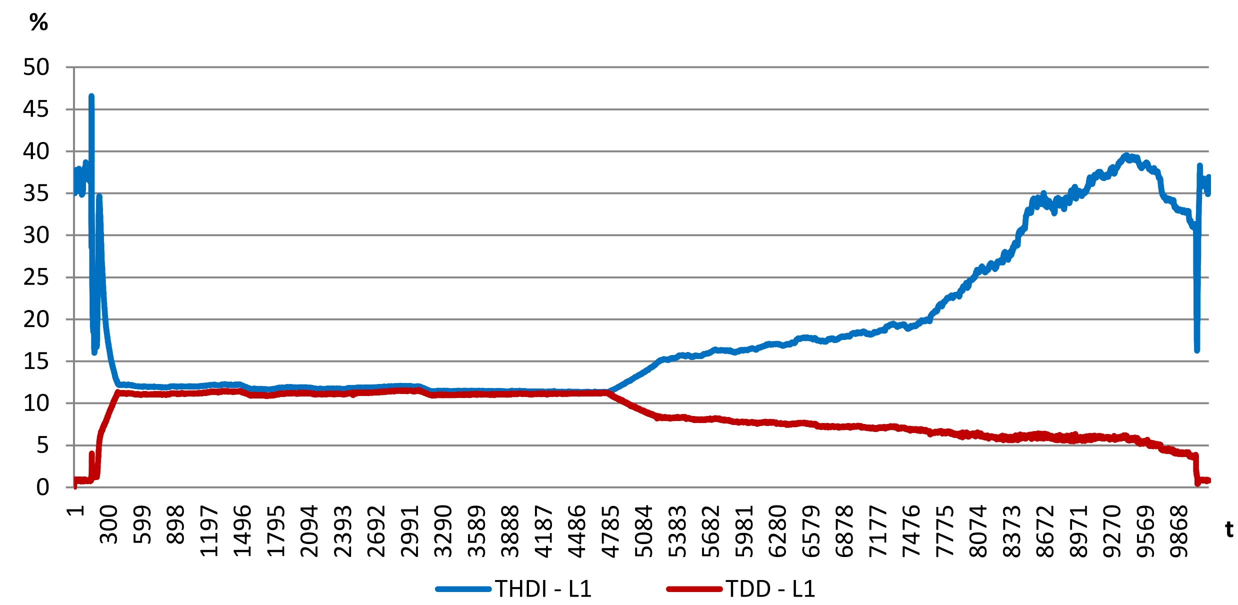

Figure 13 – THD_I and TDD during the charging cycle (24kWh load) – L_1

Both THD_I and TDD present the same behaviour as Figure 4. Figure 14 shows the corresponding THD_V for the same measurement also reporting slightly above 1.2%. No variations on the results are visible for these units caused by the change of the load from 18.7 to 24 kWh.

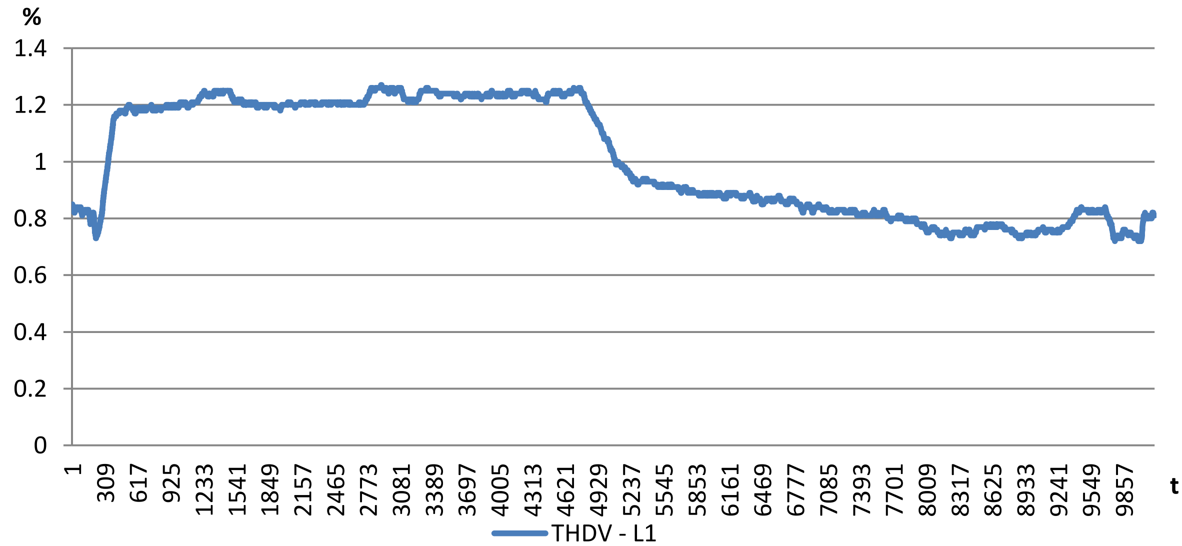

Figure 14 – THD_V during a complete charging cycle (24kWh load) – L_1

Regarding the individual harmonics, the histogram is shown in Figure 15. As expected the same harmonics have the same higher impact which are the 3rd, 5th, 7th, 9th, 11th, 13th, 17th, 23rd and 25th.

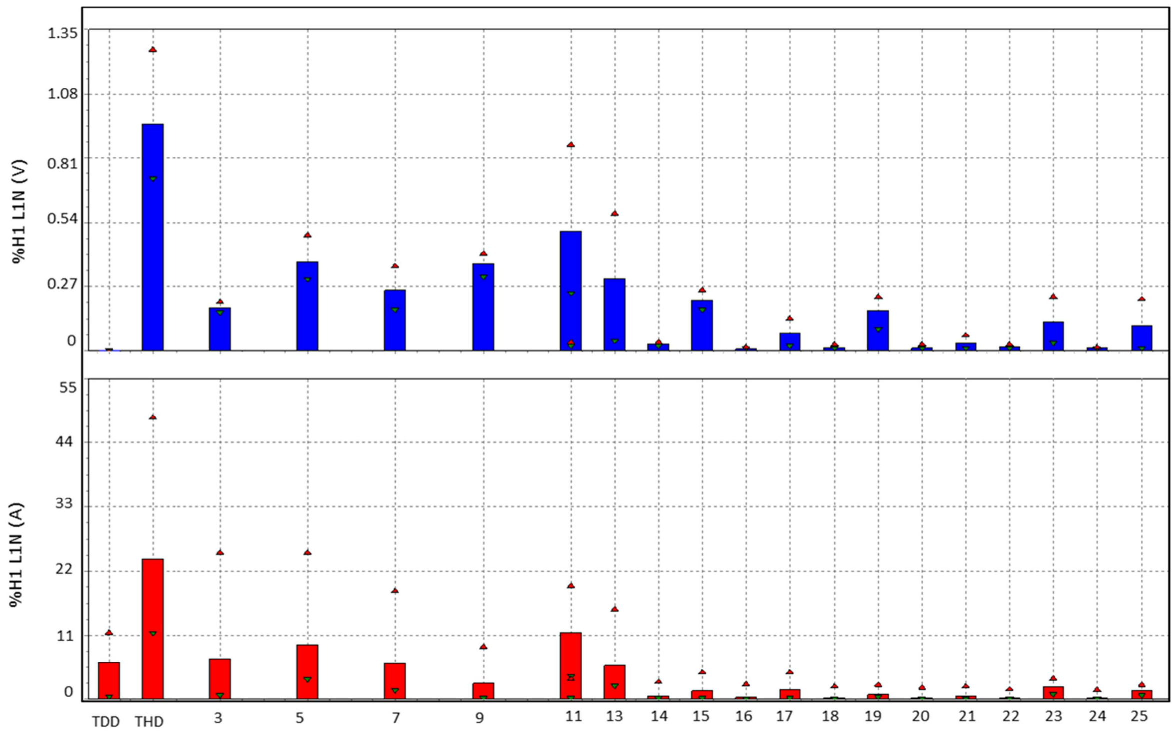

Figure 15 – Harmonic histogram from 24 kWh load

In both measurements, harmonic phase angles presented the same frequencies and phase angles range tendency. THD_I presents the same three stage tendency but during the constant stage has a value of approximately 11.4% and TDD of 12%. THD_V was 1.25% in the constant charging stage. The slight change in TDD compared to the 18.7kWh load (E-Up) may be explained by the maximum current (I_L) verified in the measurement which was 71 A instead of 67 A in the case of the E-Up.

5. Conclusions and Future work

The findings of this report suggest that EV fast charger clustering can impact power quality if the upstream short-circuit dimensioning and constraints are not properly considered.

Three goals were set for this research, first to investigate the total voltage and current harmonic distortion impact caused by fast charging an electric vehicle and standard limit compliance. Secondly to understand how the total harmonic distortions caused by fast charger/EV load varies through the charging cycle. Finally, if the distortion caused by charging more than one EV with the same charger model, decreases due to phase cancellation.

THD_V, THD_I and TDD were calculated reporting 1.2% and both 12% impacts respectively. For the charger under consideration, during the constant cycle stage, which lasted more than 15 to 20 minutes, the total values complied with the IEEE 519 and 61000-3-12/2-4 standard limits. However individual harmonics, failed to comply, mostly due to the 11^{th} and 13^{th} harmonics which are probable to break the 5.5% limit in IEEE 519 (5% and 3% respectively in IEC61000 2-4). Furthermore also the 23^{rd} and 25^{th} harmonics even though less probable, may be in violation of their own individual limits. From the results of the experiment, one can realise the harmonic limitation is a first binding condition, well before the power limitation is. This means that the number of chargers/vehicles will be limited first not by the power capacity of the upstream power transformers but by the harmonic limits for electric pollution. This of course can be said for the studied charger.

The charging cycle was characterised by three stages: an initial one lasting 2 to 3 minutes where the THD_I is very high, but the current is at its lowest point. A second stage lasting 15 to 20 minutes is characterised by a constant current demand, where THD_I and TDD maintain a similar value. Finally a third stage towards the end of the charging cycle, where a decrease of the current is observable, corresponding to an increase THD_I and decrease of the TDD. For the analysis of the standard the TDD should be applied since a variation of the current is verified and may induce in error of judgment since the relative measure may refer to different absolute values of current demand. The European standard is a bit ambiguous about this concept; hence there is an opportunity to clarify this issue in future versions.

Regarding to the result assessment with simulation of two vehicles, this implied that the phase angles should be studies in order to understand how the amplitudes of the harmonics sum. It was verified that neither a synchronisation nor a random behaviour occurred. Instead the phase angles tended to have preferential angle difference from the fundamental. Moreover, lower harmonics have higher phase angle fluctuation than higher frequency harmonics in constant current stage. From their statistical distribution study, we found that the differences between the same harmonics are lower than 90°, which mean that they will tend to add, suggesting that there is an upper limit to the number of vehicles to be considered in the system. From another point of view one can say that adding more vehicles to the same feeder will not change the THD_I or TDD, as concluded in the simulation carried out in the research. However should the number of vehicles increase, i.e. $I_{L,}$ the standard limits will decrease reaching a point where those limits are broken. It therefore depends on the robustness of the systems in terms of foreseen short circuit current and the amount of current drawn by the vehicle cluster.

After this first report it would be important to verify if other chargers have the same behaviour in terms of harmonic phase angles and distortion. Apart from the amplitude value of the harmonics which may indeed differ from manufacturer to manufacturer (since it also depends on active filtering application or not) the phase angle behaviour may be similar. Understanding this would help knowing if chargers from different manufacturers may contribute to phase cancellation or not. If no cancellation is possible it would be important to know, how many Electric vehicles/fast chargers can be connected to the same feeder depending on the robustness (I_{SC}) of the infrastructure and its ability to comply with the harmonic limitations. Do these infrastructures need harsh measures such as dedicated systems or are there optimal ranges which could be followed? Such future findings may present an opportunity to recommend on fast charging infrastructure design, adjustment of current technology or revision of standardisation.

Abbreviations

A_x	X axes component of vector A
A_y	Y axes component of vector A
B_x	X axes component of vector B
B_y	Y axes component of vector B
EV	Electric Vehicle;
$E(\theta)$	Phase Angle Mean Value
I_1	Fundamental Current
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
I_h	Individual current harmonic order
I_L	Maximum demand load current at PCC
I_{ref}	Reference current
I_{SC}	Maximum short-circuit current at PCC
J	Load
PCC	Point of Common Coupling
PHEV	Plug-in Hybrid Electric Vehicle
PQ	Power Quality
PWHC	Partial Weighted Harmonic Current
R	Resulting Amplitude of a vector
R_X	Resulting amplitude of vector X axes component
R_Y	Resulting amplitude of vector Y axes component
RSCE	Short-circuit ratio
SOC	State of Charge
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
THD_I	Current Total Harmonic Distortion
THD_V	Voltage Total Harmonic Distortion
Z	Impedance
$U_{h\Sigma}$	Resultant vector of a harmonic order
θ_h	Phase angle of a vector related to the fundamental
$\sigma(\theta)$	Phase Angle Standard Deviation

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Annex

Figures A1-A6 show the phase angle progression of phase L1 for the 4 measurements during the charging cycle, for odd harmonic orders until the 13th. They all show preferential angle ranges enabling a statistical distribution by using crystal ball. The 3rd and 9th order harmonics present higher dispersion, however mean values and stand deviations were equally obtained.

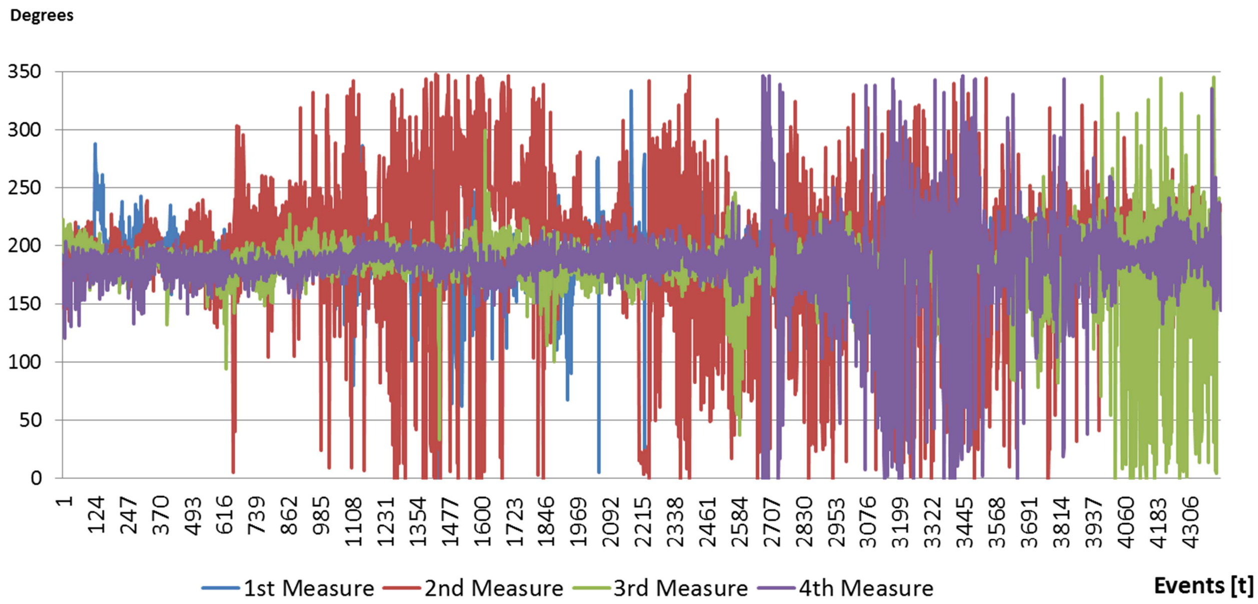

Figure A1 - Measurements 3rd Harmonic Phase Angle from 4 Measurements

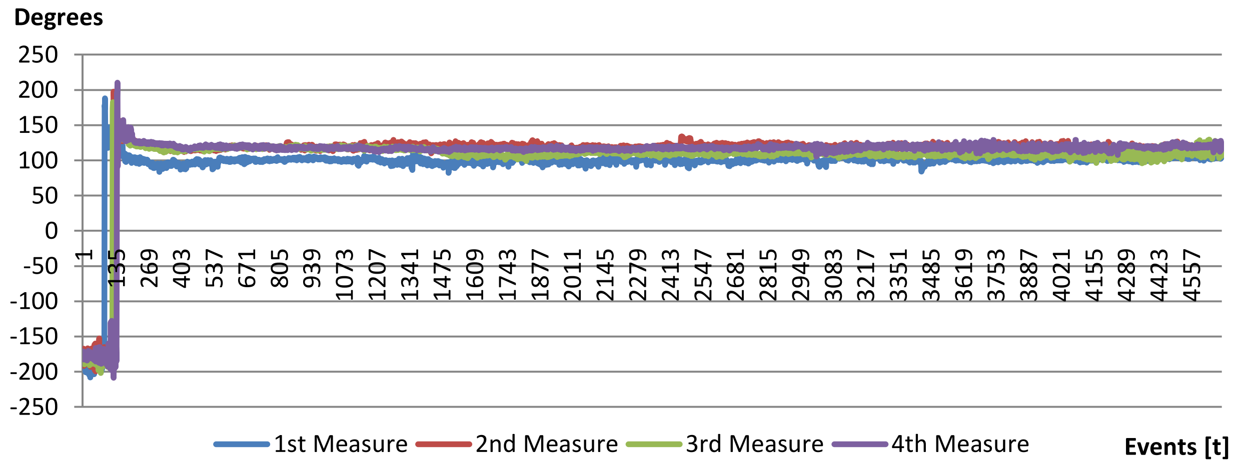

Figure A2 - Measurements 5th Harmonic Phase Angle from 4 Measurements

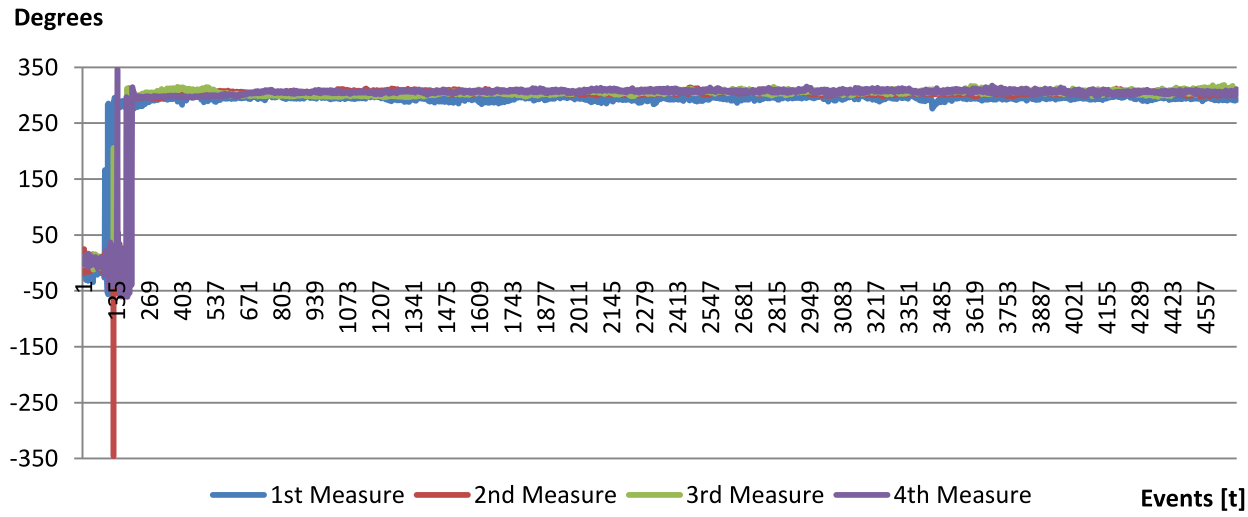

Figure A3 - Measurements 7th Harmonic Phase Angle from 4 Measurements

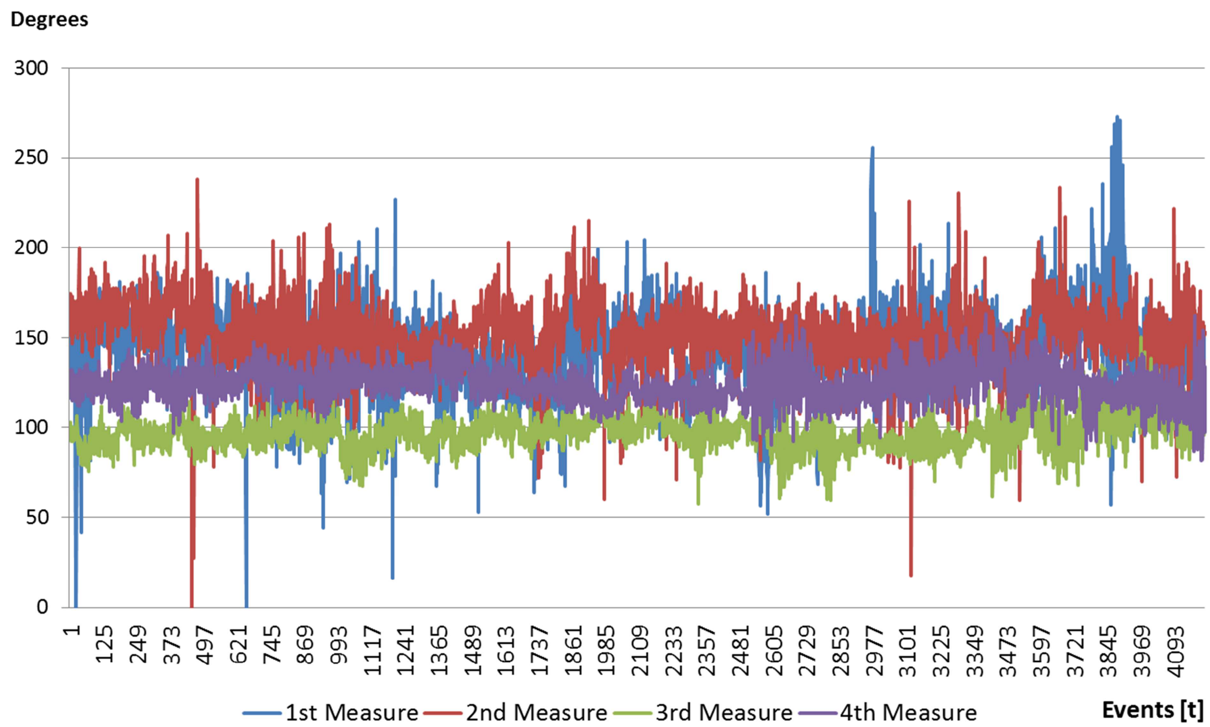

Figure A4 - Measurements 9th Harmonic Phase Angle from 4 Measurements

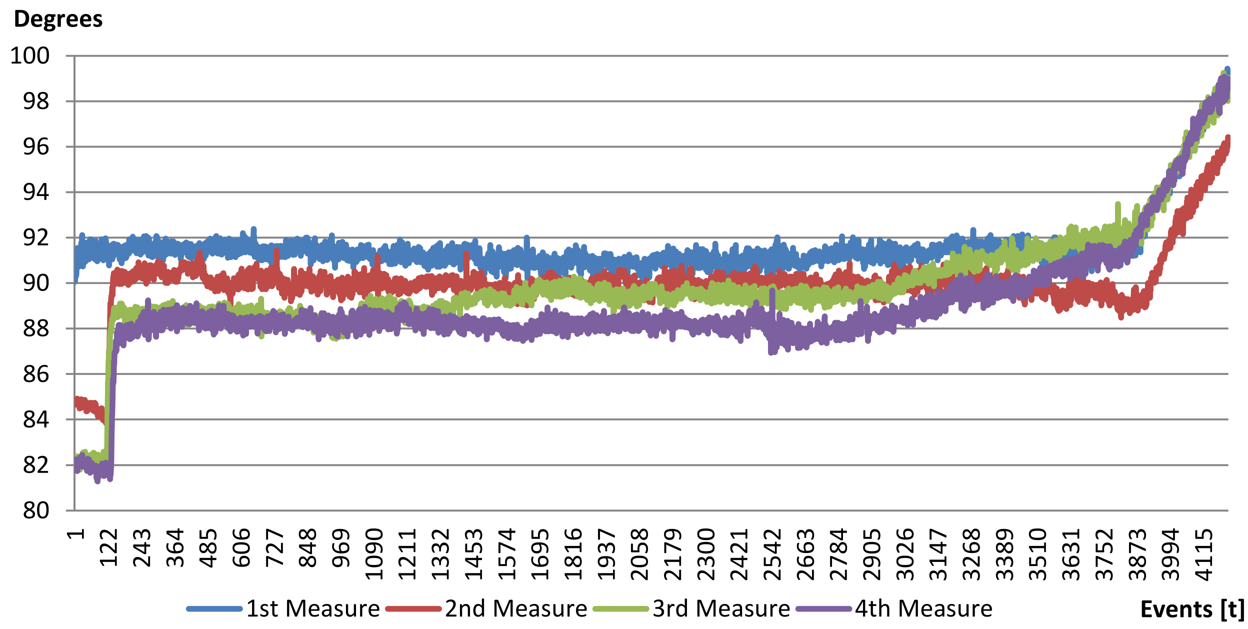

Figure A5 - Measurements 11th Harmonic Phase Angle from 4 Measurements

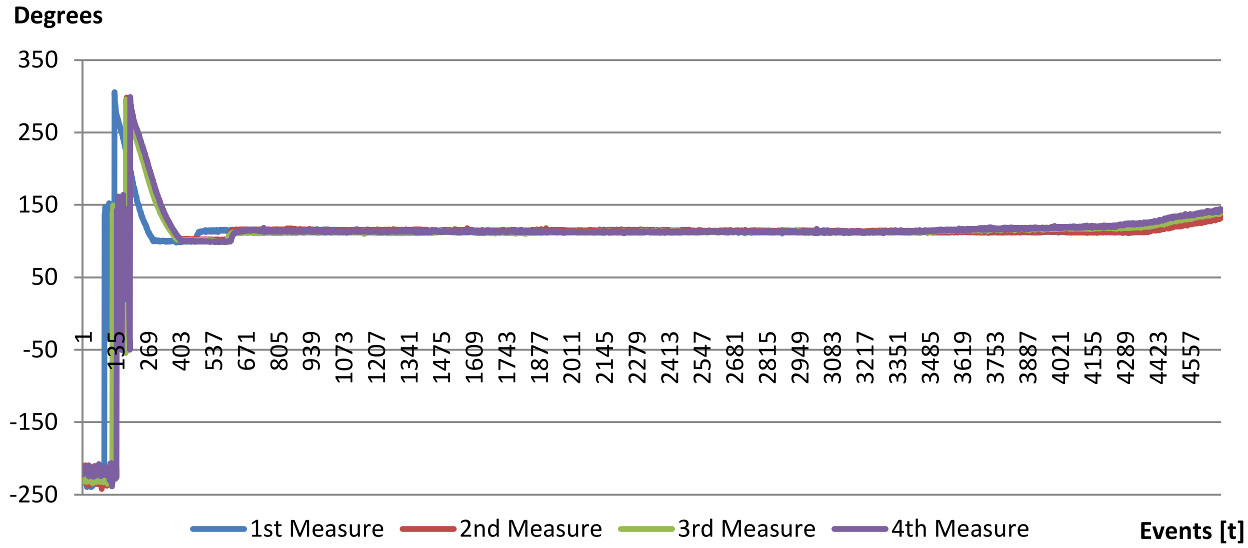

Figure A6 - Measurements 13th Harmonic Phase Angle from 4 Measurements

The Following Tables A1-A4 present 7 events during the charging cycle for each measurement respectively. All the even harmonics until the 25th are shown, as well as the THDI of each phase in the corresponding minute.

Table A1 – Reading for even harmonics and THD_I for the 1st Measurement

		Time in Charging Cycle (minutes)						
Phase 1	**Amp∟ Ang**	2	7	10	17	23	29	32
Harmonic (%)	3rd	0.58 ∟ 206.02	0.64 ∟ 206.42	0.66 ∟ 197.18	0.46 ∟ 194.84	0.45 ∟ 203.00	0.42 ∟ 201.04	0.35 ∟ 276.70
	5th	2.05 ∟ 92.90	1.93 ∟ 97.00	1.93 ∟ 94.60	2.03 ∟ 101.36	2.01 ∟ 115.30	1.87 ∟ 115.16	1.19 ∟ 121.66
	7th	0.78 ∟ 296.20	0.86 ∟ 299.78	0.85 ∟ 291.36	0.78 ∟ 294.54	1.11 ∟ 285.50	1.15 ∟ 282.80	0.63 ∟ 286.62
	9th	0.13 ∟ 144.22	0.12 ∟ 162.64	0.08 ∟ 132.72	0.09 ∟ 157.10	0.09 ∟ 95.88	0.08 ∟ 67.54	0.13 ∟ 91.92
	11th	7.12 ∟ 84.66	6.57 ∟ 91.24	6.60 ∟ 91.06	6.57 ∟ 91.80	3.70 ∟ 117.72	2.25 ∟ 124.68	1.50 ∟ 142.32
	13th	2.91 ∟ 99.46	2.38 ∟ 114.10	2.41 ∟ 112.56	2.38 ∟ 113.26	1.25 ∟ 226.88	1.67 ∟ 273.82	1.25 ∟ 296.10
	15th	0.04 ∟ 270.88	0.05 ∟ 315.54	0.03 ∟ 303.84	0.03 ∟ 1.42	0.06 ∟ 38.70	0.05 ∟ 46.82	0.05 ∟ -17.64
	17th	0.27 ∟ 282.92	0.22 ∟ 299.44	0.22 ∟ 299.86	0.23 ∟ 303.18	0.07 ∟ 79.02	0.12 ∟ 152.04	0.24 ∟ 199.86
	19th	0.39 ∟ 316.58	0.34 ∟ 324.04	0.35 ∟ 324.62	0.35 ∟ 324.74	0.14 ∟ 339.30	0.12 ∟ 313.50	0.19 ∟ 10.86
	21th	0.05 ∟ 96.94	0.07 ∟ 116.56	0.06 ∟ 114.92	0.06 ∟ 117.26	0.06 ∟ 129.48	0.07 ∟ 163.10	0.07 ∟ 134.38
	23th	1.15 ∟ 327.76	1.20 ∟ -8.68	1.19 ∟ -11.26	1.19 ∟ -9.52	0.85 ∟ 74.34	0.32 ∟ 119.98	0.31 ∟ 188.42
	25th	1.10 ∟ 345.72	1.06 ∟ 7.80	1.06 ∟ 5.16	1.06 ∟ 7.60	0.45 ∟ 119.50	0.31 ∟ 227.36	0.20 ∟ -46.64
THD (%)		**10.82**	**11.65**	**11.57**	**11.55**	**18.98**	**33.51**	**30.61**
Phase 2	**Amp∟ Ang**							
Harmonic (%)	3rd	0.62 ∟ 38.82	0.51 ∟ 38.50	0.46 ∟ 39.44	0.51 ∟ 43.68	0.38 ∟ 67.64	0.26 ∟ 61.58	0.22 ∟ 2.42
	5th	1.86 ∟ 217.82	1.82 ∟ 219.50	1.94 ∟ 218.68	1.77 ∟ 219.42	1.80 ∟ -128.68	1.75 ∟ -128.46	1.04 ∟ -117.30
	7th	0.65 ∟ 184.46	0.71 ∟ 178.68	0.69 ∟ 178.28	0.68 ∟ 176.48	1.00 ∟ 163.08	1.04 ∟ 163.46	0.48 ∟ 171.54
	9th	0.08 ∟ -95.84	0.07 ∟ -58.26	0.09 ∟ 192.06	0.06 ∟ 160.48	0.10 ∟ 195.56	0.13 ∟ 188.22	0.16 ∟ -145.70
	11th	6.87 ∟ 205.42	6.35 ∟ 211.86	6.35 ∟ 211.76	6.32 ∟ 212.04	3.62 ∟ -121.48	2.17 ∟ -114.96	1.50 ∟ -99.46
	13th	2.85 ∟ -23.38	2.29 ∟ -9.68	2.33 ∟ -11.12	2.30 ∟ -9.60	1.18 ∟ 107.20	1.66 ∟ 155.66	1.39 ∟ 176.88
	15th	0.05 ∟ 31.70	0.04 ∟ 37.72	0.04 ∟ 1.84	0.03 ∟ -12.64	0.06 ∟ -17.06	0.06 ∟ 9.20	0.04 ∟ 73.68
	17th	0.26 ∟ 54.52	0.22 ∟ 66.54	0.23 ∟ 65.36	0.22 ∟ 70.52	0.09 ∟ 175.44	0.09 ∟ -106.06	0.19 ∟ -40.70
	19th	0.36 ∟ 189.44	0.31 ∟ 202.56	0.31 ∟ 200.92	0.31 ∟ 201.76	0.08 ∟ 212.94	0.07 ∟ 151.78	0.12 ∟ -95.04
	21th	0.02 ∟ 64.72	0.03 ∟ 72.00	0.02 ∟ 29.54	0.02 ∟ -123.28	0.02 ∟ 199.76	0.02 ∟ 146.62	0.04 ∟ -167.04
	23th	1.10 ∟ 84.98	1.13 ∟ 108.94	1.12 ∟ 106.88	1.12 ∟ 109.56	0.81 ∟ 196.90	0.31 ∟ -115.94	0.27 ∟ -58.72
	25th	1.10 ∟ 223.84	1.04 ∟ -114.46	1.04 ∟ -117.04	1.04 ∟ -114.92	0.42 ∟ -1.30	0.32 ∟ 114.86	0.27 ∟ 188.38
THD (%)		**10.56**	**11.40**	**11.35**	**11.27**	**19.20**	**38.55**	**38.05**
Phase 3	**Amp∟ Ang**							
Harmonic (%)	3rd	0.46 ∟ -81.48	0.47 ∟ -26.80	0.51 ∟ -26.92	0.41 ∟ -53.06	0.40 ∟ -51.52	0.31 ∟ -45.18	0.22 ∟ -174.00
	5th	1.76 ∟ -31.66	1.68 ∟ -24.54	1.74 ∟ -22.42	1.76 ∟ -24.42	1.79 ∟ -11.68	1.70 ∟ -10.40	0.96 ∟ -5.26
	7th	0.79 ∟ 56.46	0.83 ∟ 55.32	0.85 ∟ 52.16	0.78 ∟ 51.48	1.11 ∟ 43.02	1.20 ∟ 41.38	0.66 ∟ 46.42
	9th	0.07 ∟ 93.46	0.08 ∟ -245.76	0.09 ∟ -221.80	0.05 ∟ -203.26	0.06 ∟ -169.34	0.07 ∟ -185.68	0.05 ∟ -169.28
	11th	7.07 ∟ -36.50	6.53 ∟ -29.62	6.54 ∟ -30.66	6.54 ∟ -29.58	3.71 ∟ -3.92	2.32 ∟ 1.58	1.66 ∟ 17.94
	13th	2.79 ∟ -142.84	2.22 ∟ -128.46	2.26 ∟ -130.78	2.26 ∟ -129.04	1.13 ∟ -8.66	1.65 ∟ 38.14	1.31 ∟ 56.46
	15th	0.05 ∟ -35.98	0.06 ∟ -52.62	0.06 ∟ -49.70	0.07 ∟ -50.14	0.07 ∟ -103.94	0.07 ∟ -87.98	0.06 ∟ -38.48
	17th	0.27 ∟ -196.56	0.22 ∟ -185.02	0.23 ∟ -185.62	0.23 ∟ -181.86	0.05 ∟ -84.58	0.09 ∟ 42.94	0.22 ∟ -275.62
	19th	0.33 ∟ 75.40	0.29 ∟ 84.94	0.30 ∟ 84.72	0.29 ∟ 85.72	0.06 ∟ -240.18	0.04 ∟ 43.56	0.15 ∟ -209.96
	21th	0.05 ∟ -94.14	0.05 ∟ -70.78	0.05 ∟ -81.70	0.03 ∟ -44.48	0.03 ∟ -48.20	0.04 ∟ -6.72	0.05 ∟ -27.02
	23th	1.18 ∟ -155.88	1.21 ∟ -132.16	1.20 ∟ -134.82	1.18 ∟ -132.42	0.83 ∟ -46.80	0.32 ∟ -1.86	0.33 ∟ 53.92
	25th	1.05 ∟ 104.72	1.00 ∟ -232.78	1.00 ∟ -235.70	1.00 ∟ -233.28	0.42 ∟ -118.86	0.33 ∟ -8.92	0.21 ∟ 58.66
THD (%)		**10.57**	**11.37**	**11.29**	**11.34**	**18.57**	**35.59**	**35.84**

Table A2 – Reading for even harmonics and THD_I for the 2nd Measurement

	Phase 1	Time in Charging Cycle (minutes)						
	Amp∟ Ang	2	7	10	17	23	29	32
Harmonic (%)	3rd	0.44 ∟ 199.02	0.40 ∟ 34.26	0.38 ∟ 307.56	0.75 ∟ 194.24	0.38 ∟ 225.06	0.36 ∟ 74.46	0.30 ∟ 200.18
	5th	2.64 ∟ 115.62	2.54 ∟ 126.14	2.53 ∟ 120.78	2.34 ∟ 120.44	2.40 ∟ 121.24	2.06 ∟ 129.76	1.21 ∟ 142.04
	7th	1.48 ∟ 304.60	1.33 ∟ 309.78	1.50 ∟ 305.30	1.45 ∟ 304.32	1.40 ∟ 294.64	1.31 ∟ 300.96	0.67 ∟ -36.88
	9th	0.11 ∟ 165.12	0.13 ∟ 134.60	0.10 ∟ 141.22	0.13 ∟ 164.38	0.06 ∟ 165.08	0.08 ∟ 120.02	0.12 ∟ 61.28
	11th	7.03 ∟ 84.72	6.56 ∟ 89.94	6.51 ∟ 90.24	6.61 ∟ 89.34	3.49 ∟ 116.94	2.03 ∟ 122.54	1.38 ∟ 137.74
	13th	2.95 ∟ 102.60	2.51 ∟ 114.20	2.50 ∟ 114.96	2.54 ∟ 112.68	1.32 ∟ 227.28	1.59 ∟ 272.62	1.16 ∟ 287.78
	15th	0.05 ∟ 271.70	0.07 ∟ 309.26	0.06 ∟ 280.10	0.05 ∟ 340.28	0.07 ∟ 42.58	0.08 ∟ 55.30	0.04 ∟ 37.48
	17th	0.21 ∟ 283.80	0.19 ∟ 295.78	0.17 ∟ 280.72	0.16 ∟ 272.18	0.04 ∟ 142.28	0.17 ∟ 189.82	0.30 ∟ 228.78
	19th	0.30 ∟ 320.30	0.30 ∟ 326.00	0.27 ∟ 320.68	0.25 ∟ 323.40	0.14 ∟ -17.06	0.15 ∟ -29.38	0.25 ∟ 29.08
	21th	0.05 ∟ 107.46	0.03 ∟ 103.12	0.05 ∟ 154.50	0.06 ∟ 118.76	0.07 ∟ 154.62	0.06 ∟ 167.94	0.06 ∟ 136.58
	23th	1.17 ∟ 331.36	1.19 ∟ -10.28	1.20 ∟ -10.18	1.20 ∟ 346.94	0.82 ∟ 77.48	0.32 ∟ 122.12	0.27 ∟ 186.08
	25th	1.11 ∟ 347.32	1.05 ∟ 5.06	1.06 ∟ 5.00	1.07 ∟ 2.90	0.41 ∟ 128.00	0.32 ∟ 228.92	0.18 ∟ 294.34
	THD (%)	**11.18**	**11.80**	**11.89**	**11.81**	**20.84**	**35.09**	**29.87**
	Phase 2							
	Amp∟ Ang							
Harmonic (%)	3rd	0.41 ∟ 49.80	0.53 ∟ 147.96	0.30 ∟ 119.64	0.61 ∟ 49.82	0.31 ∟ 53.82	0.28 ∟ 173.04	0.23 ∟ -12.88
	5th	2.49 ∟ -124.86	2.10 ∟ 228.54	2.40 ∟ -122.42	2.36 ∟ -119.12	2.20 ∟ -118.60	1.91 ∟ -119.72	1.08 ∟ -94.82
	7th	1.42 ∟ 185.84	1.33 ∟ 183.66	1.42 ∟ 186.18	1.31 ∟ 185.10	1.33 ∟ 174.80	1.30 ∟ 176.50	0.61 ∟ -148.40
	9th	0.07 ∟ 212.30	0.08 ∟ -103.32	0.08 ∟ -109.60	0.09 ∟ 195.28	0.11 ∟ 169.72	0.12 ∟ 162.50	0.21 ∟ -161.84
	11th	6.74 ∟ 204.92	6.31 ∟ 210.50	6.26 ∟ 210.92	6.33 ∟ 209.90	3.31 ∟ -122.04	2.03 ∟ -116.48	1.33 ∟ -106.02
	13th	2.93 ∟ -20.22	2.50 ∟ -9.14	2.48 ∟ -8.90	2.50 ∟ -11.18	1.24 ∟ 107.30	1.60 ∟ 152.52	1.26 ∟ 169.26
	15th	0.04 ∟ 79.70	0.05 ∟ 101.58	0.04 ∟ 84.12	0.04 ∟ 156.36	0.06 ∟ -39.78	0.05 ∟ -30.70	0.03 ∟ -0.60
	17th	0.19 ∟ 50.82	0.16 ∟ 59.44	0.15 ∟ 60.12	0.14 ∟ 54.86	0.05 ∟ 200.16	0.08 ∟ -63.34	0.24 ∟ -14.44
	19th	0.28 ∟ 192.72	0.24 ∟ 200.18	0.24 ∟ 197.30	0.24 ∟ 195.10	0.09 ∟ 218.74	0.10 ∟ 197.32	0.23 ∟ -73.10
	21th	0.02 ∟ -67.16	0.03 ∟ -128.52	0.03 ∟ 5.98	0.03 ∟ -61.84	0.02 ∟ -32.44	0.02 ∟ -53.22	0.06 ∟ -141.54
	23th	1.08 ∟ 88.16	1.11 ∟ 107.52	1.12 ∟ 108.30	1.11 ∟ 104.68	0.78 ∟ 198.94	0.32 ∟ -116.60	0.22 ∟ -61.88
	25th	1.10 ∟ 225.34	1.05 ∟ -117.06	1.05 ∟ -116.86	1.05 ∟ -118.78	0.39 ∟ 6.70	0.33 ∟ 111.84	0.21 ∟ 172.02
	THD (%)	**10.93**	**11.53**	**11.70**	**11.55**	**20.96**	**41.31**	**36.69**
	Phase 3							
	Amp∟ Ang							
Harmonic (%)	3rd	0.38 ∟ -66.62	0.63 ∟ -63.58	0.41 ∟ -51.64	0.50 ∟ -64.20	0.28 ∟ -59.82	0.35 ∟ -51.52	0.18 ∟ 6.98
	5th	2.43 ∟ -7.16	2.53 ∟ -10.00	2.44 ∟ -3.86	2.06 ∟ -1.32	2.14 ∟ -2.58	2.02 ∟ -0.64	0.95 ∟ 23.48
	7th	1.51 ∟ 60.40	1.29 ∟ 58.76	1.51 ∟ 61.82	1.44 ∟ 63.20	1.43 ∟ 50.92	1.30 ∟ 51.40	0.71 ∟ 76.30
	9th	0.05 ∟ 69.60	0.06 ∟ -188.92	0.07 ∟ -229.84	0.08 ∟ 108.42	0.05 ∟ -192.18	0.07 ∟ -110.50	0.05 ∟ -106.76
	11th	6.97 ∟ -36.82	6.51 ∟ -31.22	6.45 ∟ -31.16	6.54 ∟ -32.08	3.48 ∟ -4.82	2.11 ∟ 1.38	1.56 ∟ 11.86
	13th	2.85 ∟ -140.10	2.40 ∟ -129.94	2.38 ∟ -128.58	2.38 ∟ -130.48	1.18 ∟ -9.08	1.52 ∟ 36.74	1.18 ∟ 49.64
	15th	0.05 ∟ -34.18	0.05 ∟ -51.90	0.05 ∟ -34.48	0.07 ∟ -35.92	0.05 ∟ -101.16	0.07 ∟ -79.16	0.07 ∟ -37.78
	17th	0.20 ∟ -198.56	0.20 ∟ -195.22	0.16 ∟ -199.48	0.14 ∟ -208.18	0.03 ∟ 66.42	0.13 ∟ 62.78	0.30 ∟ -252.18
	19th	0.25 ∟ 78.08	0.24 ∟ 92.70	0.22 ∟ 83.38	0.21 ∟ 81.28	0.08 ∟ -252.42	0.08 ∟ 82.00	0.25 ∟ -200.24
	21th	0.03 ∟ -81.10	0.03 ∟ 19.92	0.03 ∟ -26.20	0.05 ∟ -65.76	0.03 ∟ -3.36	0.03 ∟ 14.64	0.05 ∟ 9.44
	23th	1.19 ∟ -153.78	1.21 ∟ -135.08	1.21 ∟ -134.36	1.21 ∟ -138.02	0.80 ∟ -44.66	0.32 ∟ 0.02	0.29 ∟ 49.48
	25th	1.05 ∟ 106.00	1.00 ∟ -236.44	1.01 ∟ -235.52	1.01 ∟ -237.92	0.38 ∟ -110.54	0.33 ∟ -8.92	0.18 ∟ 47.40
	THD (%)	**10.97**	**11.71**	**11.70**	**11.44**	**20.35**	**39.10**	**34.63**

Table A3 – Reading for even harmonics and THD$_I$ for the 3rd Measurement

Phase 1		Time in Charging Cycle (minutes)						
Amp∟Ang		2	7	10	17	23	29	32
Harmonic (%)	3rd	0.44 ∟ 178.38	0.44 ∟ 193.32	0.40 ∟ 189.00	0.48 ∟ 158.74	0.43 ∟ 100.98	0.44 ∟ 89.08	0.39 ∟ 113.52
	5th	2.13 ∟ 116.12	1.76 ∟ 108.34	1.77 ∟ 108.74	1.64 ∟ 108.56	1.65 ∟ 125.34	1.56 ∟ 139.14	1.15 ∟ 144.24
	7th	1.38 ∟ 309.24	0.92 ∟ 305.08	0.87 ∟ 307.16	0.90 ∟ 304.80	0.82 ∟ 300.94	0.84 ∟ 312.00	0.66 ∟ -39.26
	9th	0.14 ∟ 103.10	0.15 ∟ 95.20	0.14 ∟ 108.18	0.14 ∟ 117.54	0.11 ∟ 127.22	0.13 ∟ 160.98	0.15 ∟ 118.46
	11th	7.03 ∟ 82.26	6.53 ∟ 88.76	6.50 ∟ 89.62	6.30 ∟ 91.80	3.22 ∟ 117.00	2.24 ∟ 121.28	1.67 ∟ 127.66
	13th	3.04 ∟ 101.20	2.51 ∟ 111.50	2.50 ∟ 112.70	2.31 ∟ 117.84	1.17 ∟ 224.44	1.65 ∟ 271.16	1.46 ∟ 282.78
	15th	0.05 ∟ 314.32	0.07 ∟ 161.28	0.07 ∟ 339.78	0.07 ∟ 321.86	0.09 ∟ 44.26	0.09 ∟ 93.04	0.06 ∟ 94.50
	17th	0.24 ∟ 268.14	0.21 ∟ 290.00	0.22 ∟ 294.56	0.20 ∟ 295.88	0.04 ∟ 48.36	0.09 ∟ 172.60	0.19 ∟ 209.40
	19th	0.34 ∟ 318.20	0.32 ∟ 323.04	0.34 ∟ 325.20	0.32 ∟ 328.16	0.14 ∟ -6.12	0.11 ∟ -10.88	0.18 ∟ 13.96
	21th	0.02 ∟ 107.60	0.03 ∟ 126.62	0.03 ∟ 131.66	0.04 ∟ 109.72	0.06 ∟ 135.28	0.09 ∟ 160.94	0.07 ∟ 153.52
	23th	1.16 ∟ 326.32	1.18 ∟ 344.82	1.17 ∟ 167.32	1.18 ∟ -5.82	0.77 ∟ 76.62	0.37 ∟ 125.42	0.29 ∟ 157.38
	25th	1.10 ∟ 344.14	1.07 ∟ 1.14	1.06 ∟ 3.72	1.04 ∟ 10.02	0.37 ∟ 119.44	0.31 ∟ 232.50	0.27 ∟ 278.26
THD (%)		**10.89**	**11.32**	**11.33**	**11.61**	**18.87**	**30.74**	**31.07**
Phase 2								
Amp∟Ang								
Harmonic (%)	3rd	0.36 ∟ 48.10	0.35 ∟ 61.86	0.34 ∟ 59.86	0.29 ∟ 64.58	0.47 ∟ 65.96	0.43 ∟ 26.52	0.28 ∟ -53.66
	5th	2.00 ∟ -129.20	1.65 ∟ 222.24	1.60 ∟ 223.56	1.61 ∟ 221.00	1.21 ∟ -124.02	1.07 ∟ -104.80	1.02 ∟ -100.30
	7th	1.20 ∟ 192.36	0.74 ∟ 188.08	0.71 ∟ 189.38	0.72 ∟ 184.98	0.71 ∟ 182.22	0.68 ∟ 189.56	0.51 ∟ -160.52
	9th	0.13 ∟ -121.08	0.13 ∟ 224.34	0.14 ∟ -119.64	0.14 ∟ -119.42	0.10 ∟ 205.70	0.09 ∟ 198.92	0.13 ∟ -153.10
	11th	6.79 ∟ 202.72	6.33 ∟ 209.40	6.30 ∟ 210.22	6.10 ∟ 212.08	3.05 ∟ -122.32	2.05 ∟ -119.16	1.73 ∟ -113.48
	13th	3.04 ∟ -21.24	2.50 ∟ -11.62	2.48 ∟ -10.48	2.30 ∟ -5.58	1.11 ∟ 105.52	1.57 ∟ 151.20	1.52 ∟ 164.22
	15th	0.05 ∟ 97.84	0.05 ∟ 199.30	0.05 ∟ 164.16	0.05 ∟ 109.24	0.06 ∟ -40.32	0.07 ∟ -32.98	0.06 ∟ -18.50
	17th	0.20 ∟ 38.80	0.21 ∟ 59.96	0.21 ∟ 63.30	0.20 ∟ 62.20	0.06 ∟ 150.90	0.04 ∟ -68.10	0.12 ∟ -38.74
	19th	0.32 ∟ 189.60	0.29 ∟ 195.96	0.30 ∟ 197.54	0.27 ∟ 200.38	0.09 ∟ 217.36	0.05 ∟ 199.70	0.10 ∟ -99.40
	21th	0.03 ∟ 90.90	0.02 ∟ 81.54	0.02 ∟ 117.40	0.03 ∟ 165.88	0.03 ∟ 127.00	0.03 ∟ 2.96	0.04 ∟ 184.26
	23th	1.06 ∟ 83.98	1.08 ∟ 104.18	1.08 ∟ 106.38	1.08 ∟ 113.06	0.70 ∟ 198.58	0.33 ∟ -118.78	0.29 ∟ -84.54
	25th	1.10 ∟ 221.68	1.06 ∟ -120.46	1.05 ∟ -118.22	1.03 ∟ -112.00	0.36 ∟ 2.32	0.31 ∟ 114.52	0.31 ∟ 156.34
THD (%)		**10.65**	**11.14**	**11.13**	**11.42**	**18.58**	**33.00**	**38.04**
Phase 3								
Amp∟Ang								
Harmonic (%)	3rd	0.46 ∟ -56.66	0.49 ∟ -50.60	0.48 ∟ -51.44	0.58 ∟ -55.26	0.54 ∟ -93.38	0.57 ∟ -113.90	0.27 ∟ -58.44
	5th	2.05 ∟ -7.12	1.72 ∟ -18.34	1.70 ∟ -17.10	1.69 ∟ -19.02	1.39 ∟ -11.48	1.22 ∟ -7.36	1.01 ∟ 17.76
	7th	1.36 ∟ 70.64	0.86 ∟ 66.92	0.83 ∟ 65.94	0.82 ∟ 61.78	0.86 ∟ 53.78	0.80 ∟ 62.82	0.59 ∟ 77.14
	9th	0.07 ∟ -183.36	0.07 ∟ -167.44	0.07 ∟ -219.54	0.09 ∟ -227.02	0.06 ∟ -164.12	0.07 ∟ 3.76	0.08 ∟ -104.30
	11th	6.95 ∟ -38.88	6.48 ∟ -32.20	6.45 ∟ -31.26	6.28 ∟ -29.38	3.24 ∟ -4.46	2.25 ∟ 0.66	1.84 ∟ 7.08
	13th	2.96 ∟ -141.82	2.41 ∟ -132.24	2.40 ∟ -131.00	2.19 ∟ -126.54	1.05 ∟ -14.44	1.55 ∟ 31.50	1.44 ∟ 45.08
	15th	0.06 ∟ -49.86	0.04 ∟ -20.62	0.05 ∟ -43.36	0.05 ∟ -61.56	0.06 ∟ -113.54	0.08 ∟ -66.40	0.07 ∟ -36.18
	17th	0.23 ∟ -216.76	0.22 ∟ -188.20	0.22 ∟ -190.58	0.22 ∟ -189.92	0.04 ∟ -128.12	0.05 ∟ 58.18	0.18 ∟ -272.68
	19th	0.28 ∟ 72.12	0.27 ∟ 81.30	0.27 ∟ 84.24	0.26 ∟ 90.44	0.07 ∟ -231.62	0.04 ∟ -246.68	0.13 ∟ -197.42
	21th	0.03 ∟ -85.54	0.03 ∟ -66.98	0.03 ∟ -48.78	0.04 ∟ -45.62	0.03 ∟ -49.82	0.05 ∟ -24.84	0.04 ∟ -26.50
	23th	1.14 ∟ -159.24	1.15 ∟ -139.72	1.16 ∟ -137.16	1.16 ∟ -130.56	0.74 ∟ -45.78	0.36 ∟ 0.48	0.31 ∟ 30.80
	25th	1.05 ∟ 102.68	1.02 ∟ -239.70	1.02 ∟ -237.28	0.98 ∟ -231.46	0.36 ∟ -119.76	0.32 ∟ -10.52	0.27 ∟ 29.96
THD (%)		**10.70**	**11.14**	**11.14**	**11.47**	**18.59**	**31.99**	**35.72**

Table A4 – Reading for even harmonics and THD_I for the 4^{th} Measurement

Phase 1 Amp∟Ang	Time in Charging Cycle (minutes) 2	7	10	17	23	29	32
Harmonic (%) 3rd	0.56 ∟ 178.64	0.46 ∟ 194.60	0.51 ∟ 199.42	0.57 ∟ 211.38	0.52 ∟ 164.96	0.45 ∟ 51.36	0.58 ∟ 161.78
5th	2.99 ∟ 120.80	2.18 ∟ 116.82	2.13 ∟ 117.24	2.35 ∟ 118.06	2.34 ∟ 130.70	2.23 ∟ 131.60	1.31 ∟ 156.64
7th	1.99 ∟ 298.80	1.12 ∟ 308.38	1.16 ∟ 304.76	1.29 ∟ 301.00	1.36 ∟ 301.70	1.52 ∟ 301.02	1.11 ∟ -36.88
9th	0.15 ∟ 120.92	0.15 ∟ 126.40	0.17 ∟ 115.34	0.14 ∟ 127.86	0.11 ∟ 103.70	0.12 ∟ 147.08	0.16 ∟ 82.40
11th	7.11 ∟ 82.24	6.62 ∟ 89.16	6.64 ∟ 88.34	6.46 ∟ 90.28	3.50 ∟ 115.14	2.24 ∟ 119.66	1.49 ∟ 132.10
13th	3.05 ∟ 99.24	2.50 ∟ 113.78	2.52 ∟ 112.64	2.37 ∟ 118.76	1.33 ∟ 222.90	1.65 ∟ 264.94	1.18 ∟ 278.80
15th	0.07 ∟ 306.00	0.08 ∟ 312.12	0.08 ∟ 312.92	0.08 ∟ 323.60	0.08 ∟ 12.96	0.06 ∟ 36.62	0.06 ∟ 244.70
17th	0.13 ∟ 275.18	0.18 ∟ 293.56	0.17 ∟ 290.74	0.15 ∟ 280.36	0.05 ∟ 152.50	0.14 ∟ 187.38	0.34 ∟ 229.28
19th	0.21 ∟ 316.36	0.31 ∟ 330.54	0.30 ∟ 331.50	0.29 ∟ 334.62	0.16 ∟ -9.98	0.15 ∟ -19.74	0.32 ∟ 24.58
21th	0.02 ∟ 115.96	0.03 ∟ 110.78	0.03 ∟ 136.18	0.04 ∟ 134.70	0.05 ∟ 135.80	0.06 ∟ 158.42	0.05 ∟ 116.56
23th	1.16 ∟ 323.50	1.21 ∟ 346.80	1.20 ∟ 345.14	1.22 ∟ -7.64	0.82 ∟ 74.40	0.37 ∟ 115.92	0.24 ∟ 162.28
25th	1.12 ∟ 340.32	1.05 ∟ 2.72	1.05 ∟ 1.10	1.03 ∟ 8.72	0.42 ∟ 120.64	0.32 ∟ 218.94	0.14 ∟ 261.72
THD (%)	**11.33**	**11.65**	**11.59**	**12.14**	**20.73**	**35.26**	**31.88**
Phase 2 Amp∟Ang							
Harmonic (%) 3rd	0.37 ∟ 77.42	0.40 ∟ 58.18	0.37 ∟ 49.24	0.56 ∟ 54.44	0.43 ∟ 73.82	0.30 ∟ 87.04	0.30 ∟ 194.14
5th	2.94 ∟ -125.52	2.06 ∟ -126.84	1.99 ∟ -124.42	2.17 ∟ -122.40	2.12 ∟ -114.92	2.15 ∟ -113.76	1.50 ∟ -116.64
7th	1.78 ∟ 176.72	0.95 ∟ 185.80	0.94 ∟ 186.10	1.10 ∟ 183.32	1.19 ∟ 181.18	1.42 ∟ 178.66	0.92 ∟ -163.94
9th	0.09 ∟ -123.82	0.08 ∟ 217.50	0.09 ∟ 213.94	0.07 ∟ -127.06	0.08 ∟ 218.28	0.07 ∟ 138.36	0.12 ∟ -157.08
11th	6.81 ∟ 202.86	6.37 ∟ 209.64	6.40 ∟ 208.70	6.19 ∟ 211.00	3.36 ∟ -123.96	2.20 ∟ -119.62	1.44 ∟ -105.94
13th	3.03 ∟ -23.68	2.45 ∟ -9.38	2.47 ∟ -10.06	2.28 ∟ -4.90	1.27 ∟ 106.28	1.67 ∟ 147.60	1.24 ∟ 165.66
15th	0.06 ∟ 130.82	0.05 ∟ 138.36	0.06 ∟ 116.82	0.05 ∟ 153.82	0.04 ∟ -32.04	0.06 ∟ -15.82	0.06 ∟ 13.50
17th	0.14 ∟ 38.88	0.18 ∟ 62.80	0.16 ∟ 57.04	0.15 ∟ 55.20	0.05 ∟ 184.08	0.07 ∟ -55.44	0.23 ∟ -13.06
19th	0.21 ∟ 187.66	0.30 ∟ 203.74	0.28 ∟ 205.66	0.27 ∟ 205.90	0.11 ∟ 218.86	0.10 ∟ 197.06	0.24 ∟ -96.18
21th	0.03 ∟ 88.72	0.02 ∟ 144.22	0.03 ∟ 95.54	0.02 ∟ 85.16	0.03 ∟ 150.94	0.03 ∟ -139.04	0.06 ∟ -134.24
23th	1.07 ∟ 81.10	1.10 ∟ 105.04	1.10 ∟ 103.16	1.12 ∟ 110.50	0.76 ∟ 196.52	0.36 ∟ -119.12	0.27 ∟ -67.16
25th	1.11 ∟ 219.10	1.04 ∟ -118.34	1.05 ∟ -120.42	1.02 ∟ -112.16	0.41 ∟ 1.72	0.32 ∟ 102.56	0.17 ∟ 160.60
THD (%)	**11.10**	**11.38**	**11.35**	**11.89**	**20.91**	**39.89**	**40.87**
Phase 3 Amp∟Ang							
Harmonic (%) 3rd	0.52 ∟ -39.36	0.44 ∟ -57.44	0.48 ∟ -47.84	0.41 ∟ -46.30	0.52 ∟ -47.64	0.46 ∟ -72.62	0.65 ∟ -8.80
5th	2.93 ∟ -2.30	2.03 ∟ -6.92	2.01 ∟ -5.88	2.09 ∟ -5.06	2.07 ∟ 6.00	2.24 ∟ 3.32	1.65 ∟ 26.32
7th	1.87 ∟ 57.62	1.03 ∟ 65.48	1.02 ∟ 65.06	1.23 ∟ 62.24	1.31 ∟ 61.84	1.44 ∟ 57.68	0.98 ∟ 81.72
9th	0.05 ∟ -130.86	0.06 ∟ -117.96	0.07 ∟ -127.86	0.05 ∟ -154.04	0.09 ∟ -149.80	0.08 ∟ -126.40	0.11 ∟ -136.88
11th	6.99 ∟ -38.88	6.54 ∟ -32.08	6.57 ∟ -32.80	6.36 ∟ -30.74	3.51 ∟ -6.30	2.33 ∟ -2.30	1.56 ∟ 9.26
13th	2.93 ∟ -143.70	2.36 ∟ -129.70	2.38 ∟ -129.88	2.20 ∟ -123.72	1.24 ∟ -12.46	1.64 ∟ 28.70	1.25 ∟ 46.54
15th	0.05 ∟ -21.54	0.04 ∟ 0.64	0.05 ∟ -24.76	0.04 ∟ 4.30	0.05 ∟ -82.96	0.06 ∟ -67.58	0.07 ∟ 20.70
17th	0.15 ∟ -207.24	0.19 ∟ -191.40	0.19 ∟ -192.32	0.16 ∟ -200.00	0.03 ∟ 17.86	0.11 ∟ 72.40	0.33 ∟ -256.88
19th	0.17 ∟ 66.42	0.26 ∟ 87.08	0.25 ∟ 89.04	0.23 ∟ 89.66	0.08 ∟ -241.80	0.07 ∟ 82.62	0.24 ∟ -204.04
21th	0.04 ∟ -83.20	0.03 ∟ -70.40	0.04 ∟ -58.56	0.04 ∟ -63.12	0.04 ∟ -36.36	0.04 ∟ -8.34	0.05 ∟ 36.62
23th	1.17 ∟ -161.42	1.19 ∟ -138.40	1.19 ∟ -139.88	1.21 ∟ -132.18	0.79 ∟ -48.42	0.36 ∟ -5.84	0.24 ∟ 52.36
25th	1.08 ∟ 99.56	1.01 ∟ -237.84	1.01 ∟ -239.92	1.00 ∟ -231.86	0.41 ∟ -118.40	0.33 ∟ -19.10	0.18 ∟ 29.44
THD (%)	**11.10**	**11.38**	**11.35**	**11.82**	**20.31**	**37.56**	**37.97**

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