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Fast charging diversity impact on total harmonic distortion due to phase cancellation effect

Fast Charger's testing experimental results

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Fast charging diversity impact on total harmonic distortion due to phase cancellation effect - Fast Charger's testing experimental results

Full charging cycles were performed in the studied chargers and THD_V and THD_I were observed. From the measurements it can be observed that the phase angles vary within a preferential range, i.e. remain within a range which is actually <90˚of amplitude. Two of the Chargers, working individually, failed to comply with the standards. Charger A barely makes it in terms of TDD and Charger C is out of the limit. In terms of individual harmonics also Charger A and Charger C are out of the limit of 4.5% for the 11th and 13th harmonics. The next step of the research will be to obtain the statistical distribution of each of the phase angles for all Chargers and perform simulations with different scenarios. Results so far suggest that stand alone Chargers with low short circuit values are recommended to have filters <13% THD.

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Executive summary

Road vehicles' electrification success depends on the charging infrastructure efficacy to support consumers and mitigate driving range limitations. Charging at high power means reducing the time it takes to charge the vehicles' battery. However using high power non-linear devices in low voltage grids may cause power quality problems, namely harmonic distortions.

In Europe, manufacturers are exploring different options of power in fast charging (higher than 50kW). This represents new challenges on the grid for infrastructure design, dimensioning and verifying standard compliance, in particular when such infrastructures allow multiple chargers to work simultaneously.

In 2015 the JRC conducted and published a report and scientific paper describing the methodology, research and findings [1] *regarding grid harmonic impact of multiple electric vehicle fast charging.*

Three goals were set for such research. First, to investigate the total voltage and current harmonic distortion impact caused by fast charging an electric vehicle and standard limit compliance. Second, understand how the total harmonic distortions caused by fast Charger/EV load vary through the charging cycle. Finally, simulate if the distortions caused by charging more than one EV with the same Charger model simultaneously, would decrease due to phase cancellation.

The study concluded that the primary limitation of the number of Chargers/vehicles in a cluster is not the power capacity of the upstream power transformers, but the harmonic limits for electricity pollution. The study also strongly suggests that for the standards limit analysis the TDD should be applied instead of the THD_I *since there is a misleading variation of the current during the vehicles' charging cycle. Regarding the resulting assessment with the simulation of two vehicles, it was verified that neither a synchronisation nor a random behaviour occurred in harmonic phase angles. Instead, phase angles tended to have preferential angle difference to the fundamental wave. From their statistical distribution study, one can observe that the differences between the same harmonic order (of each measurement) are lower than* 90°*, which means that with the same charger type they will add, suggesting that there is an upper limit to the number of vehicles/chargers to be considered allowable in the same charging infrastructure. Should the number of EVs increase, i.e. IL, the standard limits will decrease, reaching a point where harmonic limits are exceeded. It is therefore dependent on the robustness of the systems in terms of the foreseen short circuit current and the amount of current drawn by the vehicle cluster. As future work it was determined that the analysis should be extended to other chargers for confirmation of the suggested trend.*

Such work was developed during 2016 and now published in this report to provide technical guidance to stakeholders. This work is useful for standardisation bodies, policy makers and industry responsible for developing fast charging solutions. It is particularly useful in the planning stage before mass fast charger deployment is done. At the present stage, many chargers are being installed, mostly for pilot projects and manufacturers are only being requested to comply with the standards in what refers to their product. However when integrated in a larger system, i.e. working with other chargers, this may challenge the compliance/conformance of power quality standards. In general this research intends to answer to the following questions:

i) Do current harmonic phase angles of different fast Chargers vary within a range in each frequency?

ii) Are the current harmonic phase angles ranges in each frequency, different from Charger to Charger?

iii) Does the diversity of Chargers impact the Total harmonic distortion? Is phase cancellation verified? Do even or odd number of Chargers matter?

Results so far suggest that stand alone chargers with low short circuit values are recommended to have filters <13% THD. For multiple fast charging stations, the short circuit value should be sufficiently high so as to allow current harmonic values to be within standard limits. The preferential current harmonic phase angle was confirmed in all chargers measured. The next step of the research will be to obtain the statistical distribution of each of the phase angles for all Chargers and perform simulations with different scenarios. Among others, and to answer the research questions, the simulation stage will consider different configurations of Chargers (in number). The end goal is to evaluate the diversification of Chargers and if it reduces the THDI due to the cancellation effect.

1. Introduction

Mass increase of electric vehicles (EV) foreseen for the near future constitutes a challenge for infrastructure design and dimensioning. In a changing sector, EV integration into power grids, adds more challenges for power system operators, especially regarding power quality. It is essential to evaluate potential grid impacts due to EV integration to guarantee standard compliant grid operation.

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.

In 2015 the JRC conducted and published a report and scientific paper describing the methodology, research and findings [1] regarding grid harmonic impact of multiple electric vehicle fast charging.

Three goals were set for such research. First, to investigate the total voltage and current harmonic distortion impact caused by fast charging an electric vehicle and standard limit compliance. Second, understand how the total harmonic distortions caused by fast Charger/EV load vary through the charging cycle. Finally, simulate if the distortions caused by charging more than one EV with the same Charger model simultaneously, will decrease due to phase cancellation.

The study calculated the THD_V, THD_I and TDD reporting the former at 1.2% and the latter two at 12% impacts respectively. For the Charger considered, during the constant cycle stage, total values complied with the IEEE 519 and 61000-3-12/2-4 standard limits. However, individual harmonics failed to do so, mostly due to the 11th and 13th orders which are likely to exceed the 5.5% limit in IEEE 519 (5% and 3% respectively in IEC61000 2-4). Furthermore, also the 23rd and 25th harmonics even though less probable, may be in violation of their own individual limits.

The study concluded that the primary limitation of the number of Chargers/vehicles in a cluster is not the power capacity of the upstream power transformers, but the harmonic limits for electricity pollution. The study also strongly suggests that for the standards limit analysis the TDD should be applied instead of the THD since there is a variation of the current during the cycle. Regarding the resulting assessment with the simulation of two vehicles, it was verified that neither a synchronisation nor a random behaviour occurred in phase angles. Instead the phase angles tended to have preferential angle difference to the fundamental wave. From their statistical distribution study, one can observe that the differences between the same harmonic order (of each measurement) are lower than 90◦, which means that with the same Charger type they will add, suggesting that there is an upper limit to the number of vehicles to be considered allowable in the system. Should the number of EVs increase, i.e. IL, the standard limits will decrease, reaching a point where harmonic limits are exceeded. It is therefore dependent on the robustness of the systems in terms of the foreseen short circuit current and the amount of current drawn by the vehicle cluster.

Building upon such previous work we set out as goals for this research the following questions:

iv) Do current harmonic phase angles of different fast Chargers vary within a range in each frequency?
v) Are the current harmonic phase angles ranges in each frequency, different from Charger to Charger?
vi) Does the diversity of Chargers impact the Total harmonic distortion? Is phase cancellation verified? Do even or odd number of Chargers matter?

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 13th) are slightly higher than with low voltages, while for the lower main voltage the higher harmonics (above 15th) 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 system operators 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 CHARGER A 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. System operators 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:

- System operators 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;

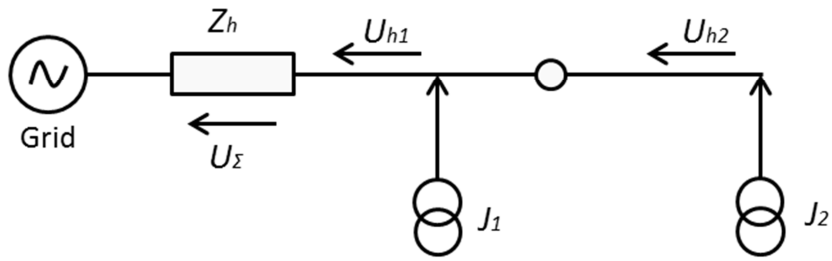
2.1. Harmonics

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):

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

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

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:

$$A_x = A_1 \cos\theta_1 \quad (7)$$

$$A_y = A_1 \sin\theta_1 \quad (8)$$

and,

$$B_x = A_2 \cos\theta_2 \quad (9)$$

$$B_y = A_2 \sin\theta_2 \quad (10)$$

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:

$$R = \sqrt{(R_X^2 + R_Y^2)} \quad (11)$$

$$\theta_R = \tan^{-1}\left(\frac{R_Y}{R_X}\right) \quad (12)$$

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/operators 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.

3. Test Design

Four sets of measurements were performed of a full electric vehicle (Nissan Leaf) using a commercial fast Chargers. Due to the vehicle's requirement, the Chademo connection was used. As measuring device the Fluke 437 Series II [31], 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 Chargers were connected to 63 A outlets, 230V, 50Hz at one end and at the other, with the Chargers manufacturer's cable, charging a 24kWh battery pack.

The vehicle was discharged by random driving cycles and a different measure was taken on different days. One can consider the temperature of the battery similar in all measurements. The Laboratory temperature was approximately 21 C°. All loads inside the car were disconnected (air conditioning, radio, lights). The 4 sets of measurements were performed from low states of charge, below 10% to > 90% SOC which lasted no less than 35 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. Two files were recorded per measurement: ii) only with the Charger connected ii) Charger plus the load (EV). 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;

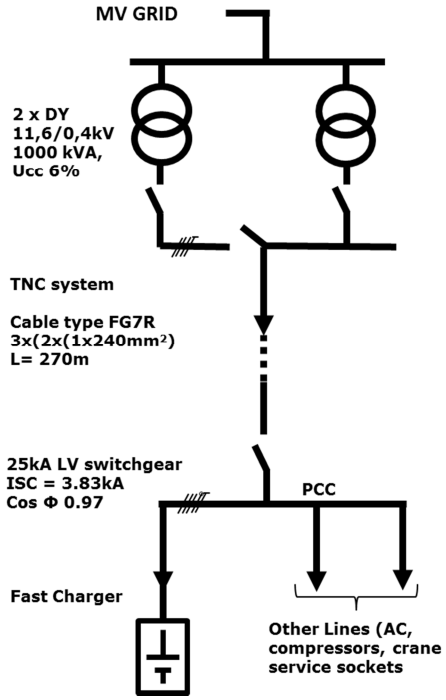
If the initial values and conditions were not met, the measurement was not considered. Frequency, Voltage nominal value variation and THD_V were required to be inferior to 3%. The upstream grid representation is shown in Figure 2, as well as the point where the measures were taken, i.e. Point of common 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



After the measurements were performed, PowerLog 4.2 software [31] 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. 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.

A sample of 4 Chargers from the CHAdeMO Association [32] was considered for testing. Figure 3 and Table 5 present the main characteristics of the Chargers tested.

Figure 3 – Pictures of the Fast Chargers tested

Charger A **Charger B** **Charger C** **Charger D**

Table 5 – Main characteristics of the fast Chargers tested

Charger	Operation	Standards/Technologies	Dimensions
Charger A – QC45	3 phases + neutral + PE; 400 Vac ± 10 %; 50 Hz; 73 A, 50 kVA; PF 0,98; Efficiency > 0.93%; DC power up to 50 kW; AC power up to 43 kVA; Max DC Output 50 kW; Max DC current 120 A	JEVS G104 (CHAdeMO) IEC61851-23 PLC (CCS / Combo-2) IEC61851-1 (AC) JEVS G105 (CHAdeMO) Combo T2 (CCS / Combo-2) IEC62196 Type-2 OCPP (1.2; 1.5) and others	Dimensions: 600 x 600 x 1800 mm; Weight: 600 Kg; Noise <55dB 6.4" TFT Color screen
Charger B - Pulse QC 50	Nominal voltage (U) : 400V AC; Nominal current (I) : 80A; AC 43kW / DC 50kW; Efficiency rate of 96 %; 400V three-phases AC (neutral system TT)	Mode 3 and 4 IEC 61851-1:2010 NF EN 61851-22:2002 IEC 62196-1:2012 IEC 61851-23:2014 Vehicle communication - CHAdéMO : BUS CAN compatible- COMBO 2 : CPL compatible - AC : Mode 3 and simplified Mode 3	Backlit LCD graphic screen (2 lines) Weight : 250kg / with extension 350kg Noise: 60dBa
Charger C - CCL-QPC-CH-CCS-AC63	3P + N + PE; 400V AC +/- 5%; 143 A (software limit control); PF >0,96; Eff: 95 % at nominal output Power; Freq: 50 / 60 Hz; Max DC output power 50 kW; Max DC current 120 A	Mode 4 (IEC-61851-23/24) Combo-2 (DIN 70121) Mode 4 (IEC-61851-23/24) JEVS G105 (IEC-92196-3) Mode3 (IEC61851-1) Type 2 (IEC6296) tethered Cable CE / Combo-2 (DIN 70121) EN61851-23 CHAdeMO rev.0.9 certified	Dimensions: 780mm x 650mm x 2060mm Weight: 445 Kg Noise: <55dB 8" HMI display
Charger D	3P + N + PE; 400V AC +/- 5%; 143 A PF >0,96; Eff: 95 % at nominal output Power; Freq: 50 / 60 Hz; Max DC output power 50 kW; Max DC current 120 A	Mode 4 (IEC-61851-23/24) Combo-2 (DIN 70121) Mode 4 (IEC-61851-23/24) JEVS G105 (IEC-92196-3) Mode3 (IEC61851-1) Type 2 (IEC6296) tethered Cable CE / Combo-2 (DIN 70121) EN61851-23 CHAdeMO	Dimensions: 780mm x 650mm x 2060mm Weight: 600 Kg

The study is not to analyse its standalone operation but instead its network integration behaviour.

4. Results and Discussion

4.1. Results from Measurements

Measurements were taken for approximately 35 minutes with 0.25 s time steps. This generated just over 8400 records for each variable. The Voltage and current harmonics histograms of the 4 Chargers are presented in Figures 4-7. All the even harmonics until the 25th are shown, as well as the TDD and THD_I of phase 1.

Figure 4 - Charger A Harmonic histogram

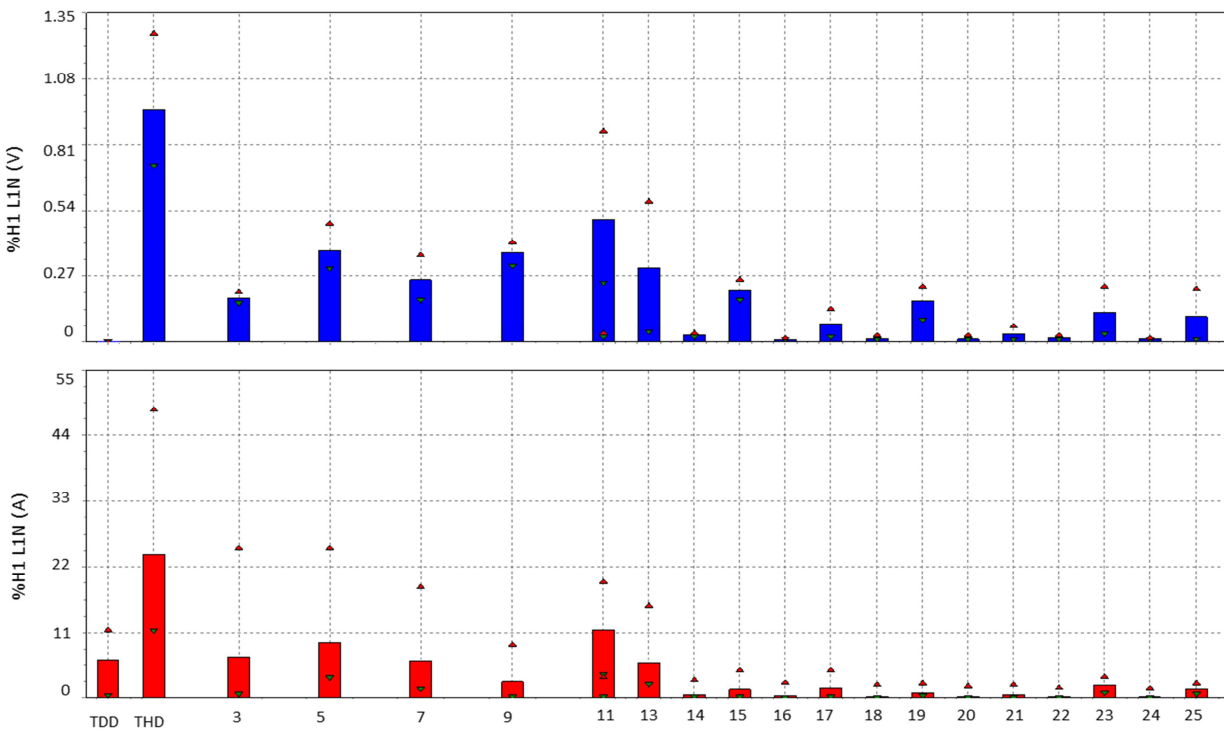


Figure 5 - Charger B Harmonic histogram

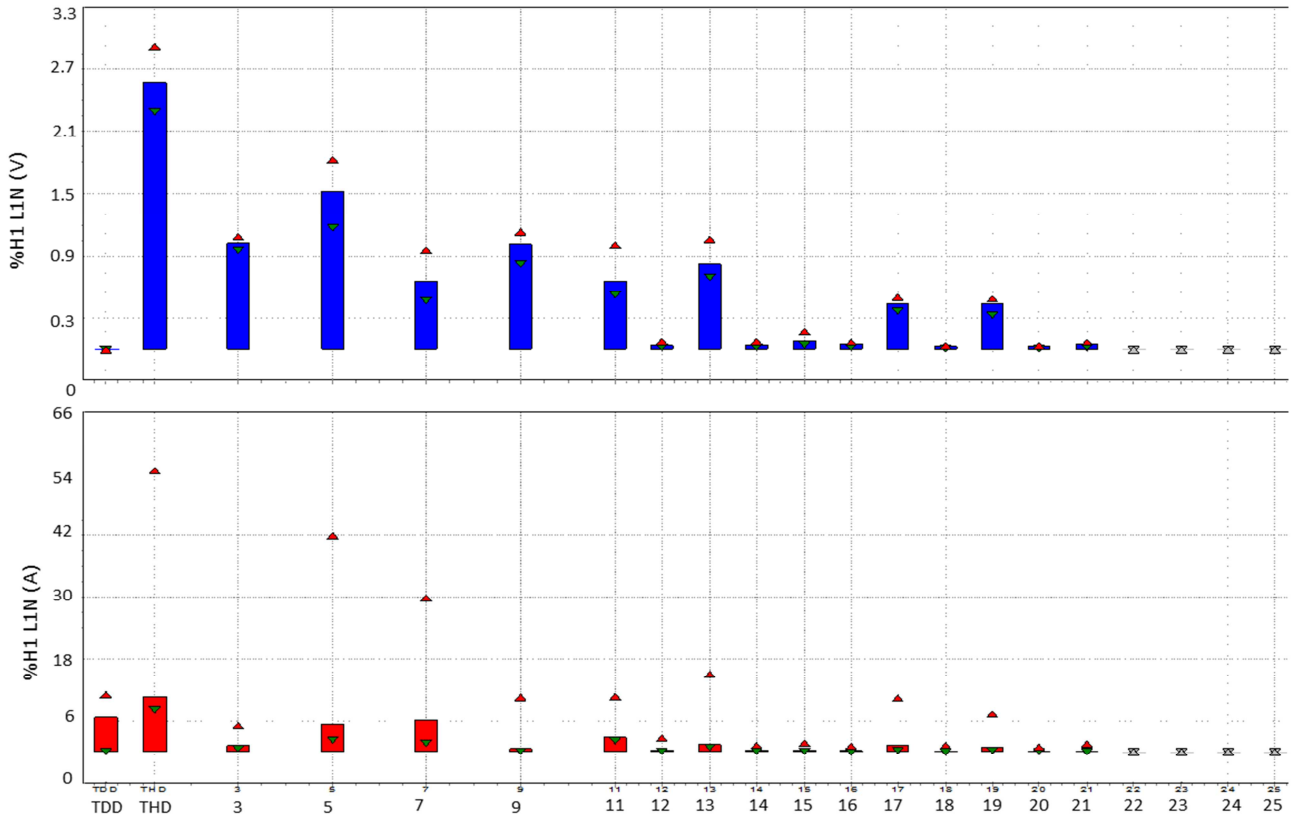


Figure 6 - Charger C Harmonic histogram

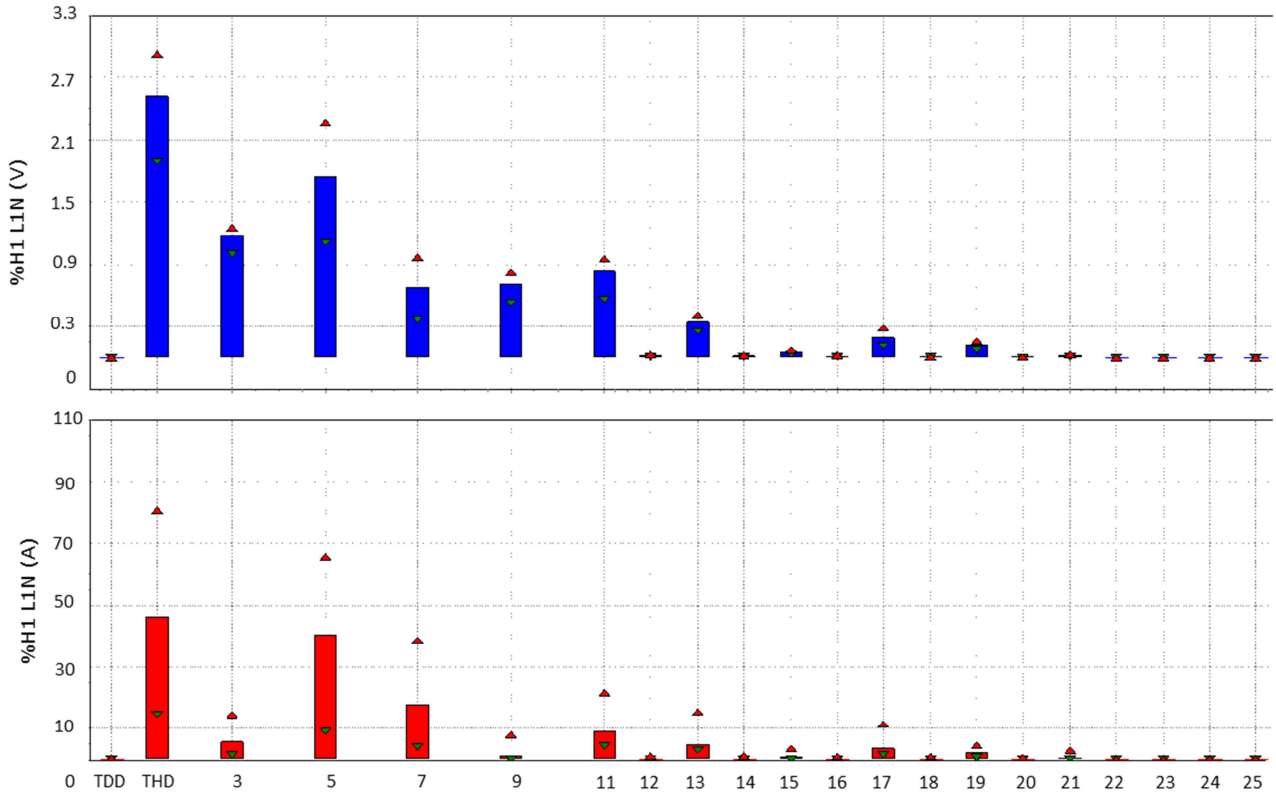
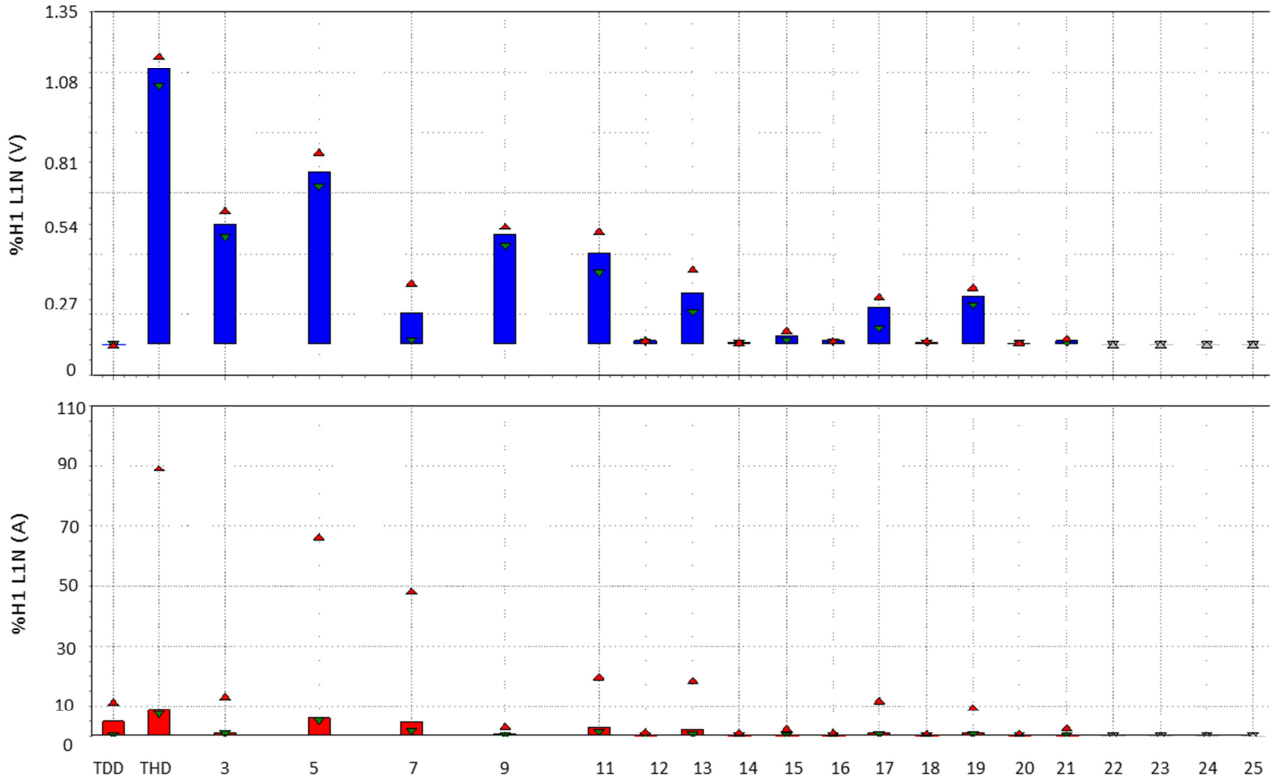
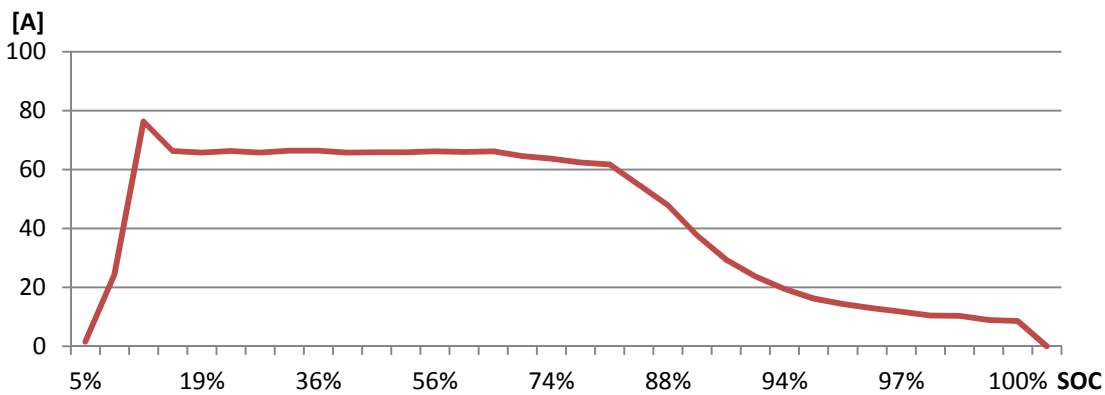


Figure 7 - Charger D Harmonic histogram



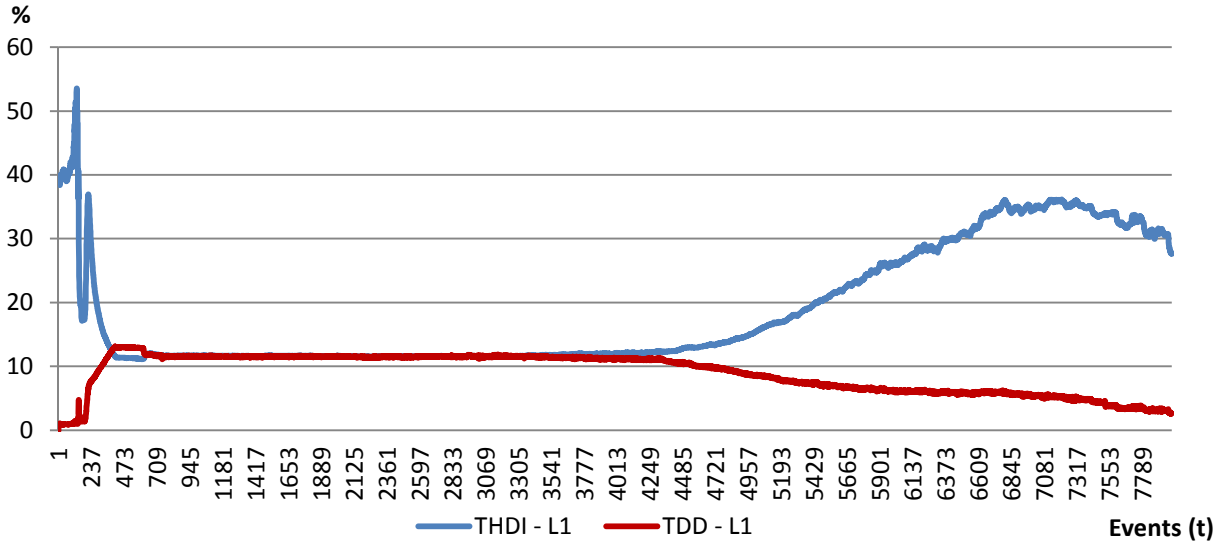
THD_V was always observed to be below 3% hence always within standard limits and it will not be further discussed. In all measurements one can verify high predominance of the 3rd , 5th, 9th, 11th and 13th harmonics. The THD_I tends to increase at the end of the charging cycle which can be explained by the decrease of the current at the end of the cycle, hence the maximum values shown. 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 90% in the Charger D, which just means it went almost to 100% of SOC, being fed by a current approximately of 1 A. For nominal current values all Chargers presented a TDD of less than 10%. Phase angles where also analysed and vary between ranges of less than 90°. The Charger A is taken as an example to explain the charging dynamics hereafter. From Figure 8 and 9 it can be observed three distinct stages.

Figure 8 – Current behaviour during a charging cycle



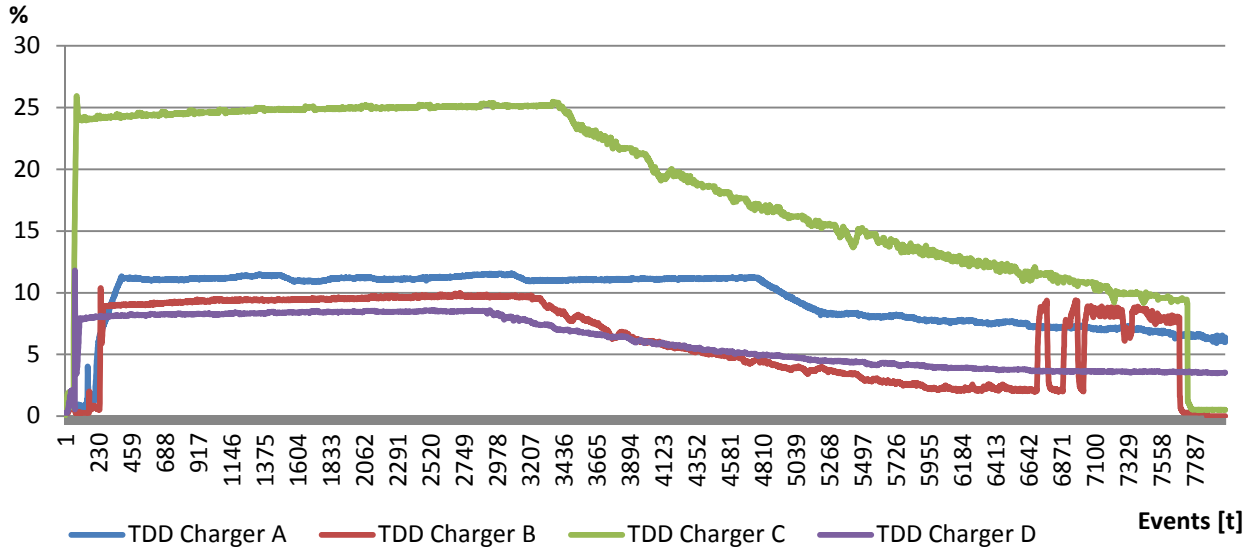
The Charger A is taken as an example to explain the charging dynamics hereafter. From Figure 8 and 9 it can be observed a first stage during the first 2-3 minutes of charging with very high TDD_I peaking to more than 50% while TDD starts low, a second stage with a constant behaviour where TDD and THD 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%. It should also be highlighted 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 9 – THD_I and TDD during the charging cycle – L_1



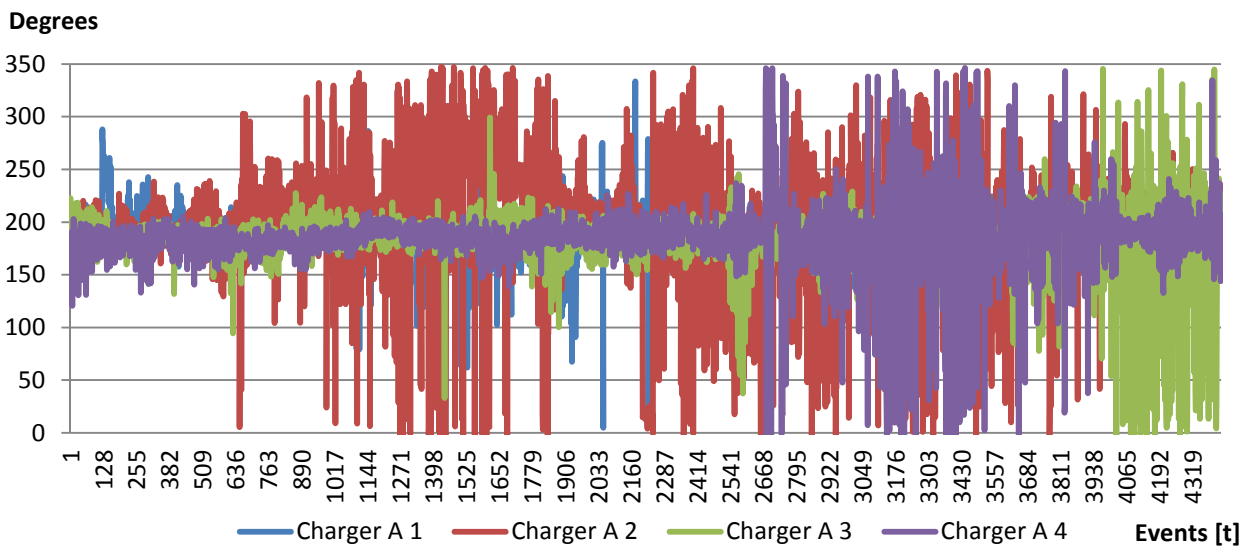
Values of both TDD and THD_I are coherent with others presented in the literature [8], [9]. For TDD calculations it is suggested in the standards that the average current for the maximum demand over the previous 12 months should be taken in to consideration. However this value was not possible to assess and so TDD calculations were based on the maximum current of 67.5 A demand during the charging cycle (even though a peak of 77 A was recorded, it only lasted for maximum of 1 minute 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. The TDD for the four Chargers tested are presented in Figure 10.

Figure 10 – THD_I and TDD during the charging cycle – L_1



For the analysis of the phase angle ranges, each odd harmonic frequency was measured four times in different charging cycles (only 3 measurements for the Charger C[1]). An example is given in Figure 11-14 present a set of harmonic phase angle ranges for all Chargers measured (corresponding to phase 1). Similarly other odd number harmonic angles are shown in the Annex A. As can be observed all angles vary within a range that 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.

Figure 11 – 3rd Harmonic phase angle ranges from Charger A - L_1



[1] According to the methodology, it was defined that if the initial conditions were not met the measurement would be discarded. We verified in fact that the voltage harmonics were not below de defined limit. This impacted on the phase angles and during the analysis process for coherency it could not be considered as a valid measurement.

Figure 12 – 3rd Harmonic phase angle ranges from Charger B - L_1

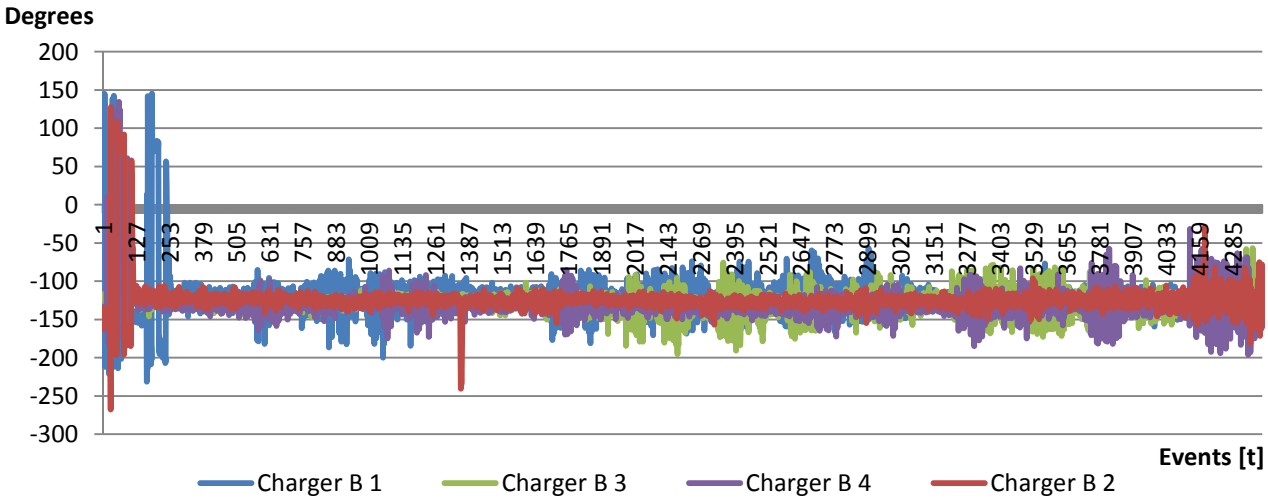


Figure 13 – 3rd Harmonic phase angle ranges from Charger C - L_1

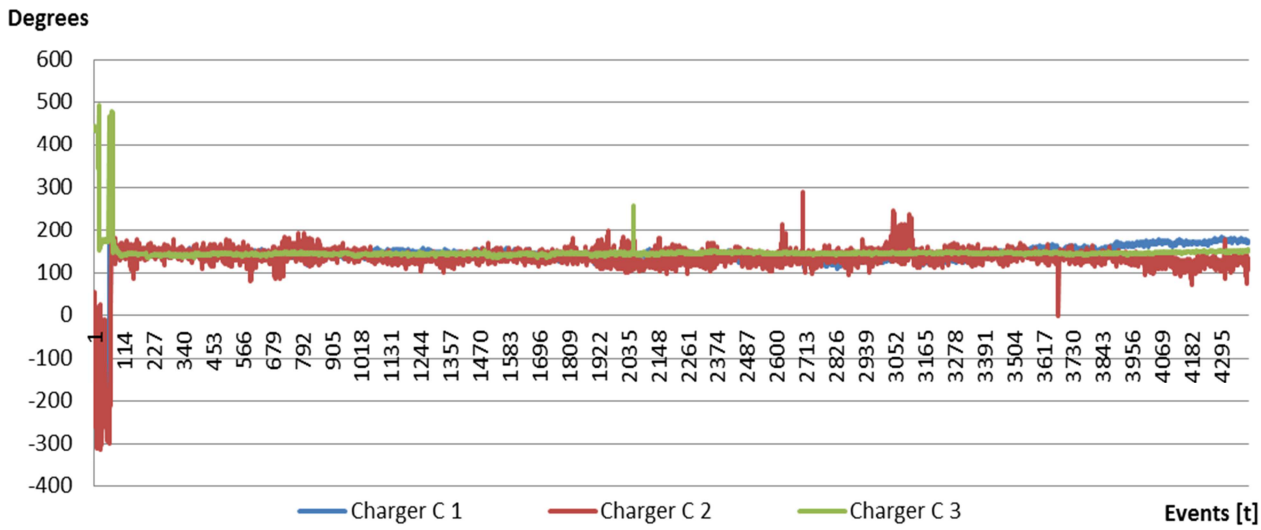
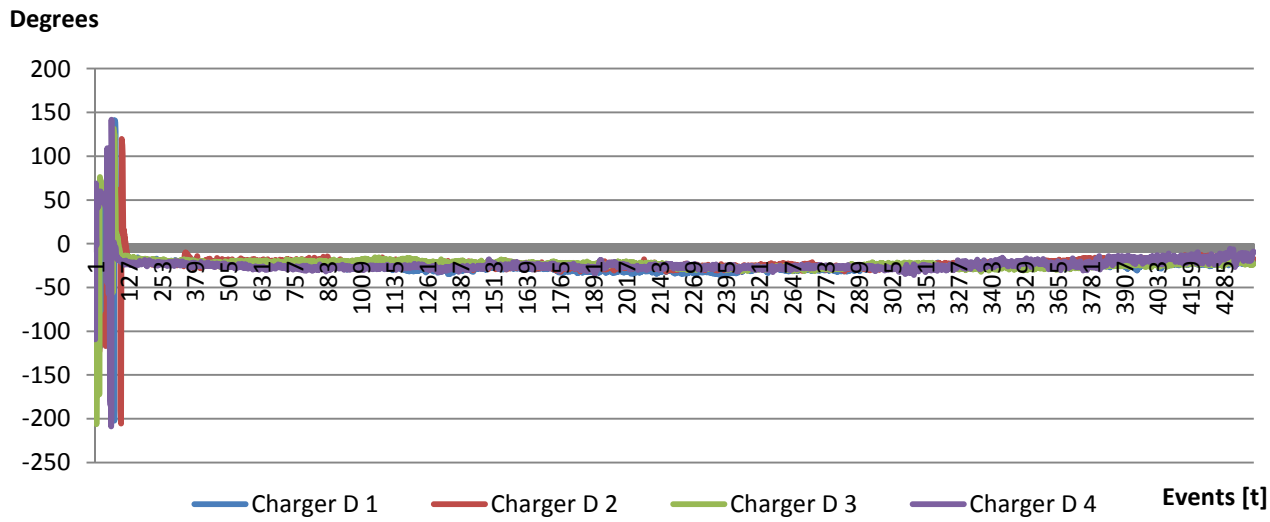


Figure 14 – 3rd Harmonic phase angle ranges from Charger D - L_1



4.2. Comparison with the standard limits

In order to identify the permitted limits for distortions in the standard the I_{SC} must be calculated. Its value was measured in the General Low Voltage Main Cabinet, which is the actual PCC under analysis. Values recorder ranged from 3830 A to 4090 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} = 3.83 kA; I_L = 67.5 A → Ratio = 56.7 A

Hence interval 50<100 should be considered if the IEEE which refers to the TDD is taken into consideration. Through the identification of the limits (TDD max 12%), it can now be seen that the Charger B and Charger D are in conformance with this limit of TDD, whereas Charger A barely makes it and Charger C is out of the limit.
In terms of individual harmonics also Charger A and Charger C are out of the limit of 4.5% for the 11th and 13th harmonics. Despite the results, the goal of this report is not to verify if the equipment is within limits since this depends on the installation they will be inserted in (Short circuit current) and in fact the harmonic distortion may be mitigated with filters in each of the equipment aiming a certain frequency. The goal is instead to study how they interact with each other, and for that simulation of different configurations is needed.

5. Conclusions and Future work

This report presents the results of the experimental activities regarding fast charging harmonic impact. This work provides technical guidance and was built upon previous work that suggested that EV fast Charger clustering can impact power quality, if the upstream short-circuit dimensioning and constraints are not properly considered. Previous work suggested that using the same time of equipment in the same facility could cause the THD_I to increase to a point where the limits imposed by the standards would be broken. In the present investigation, in order to study the impact of diversity of equipment in the same charging installation a set of 4 different fast Chargers were studied. Full charging cycles were measured 4 times per each of the 4 Chargers and the THD_V and THD_I were registers. The amplitude of each harmonic and their phase angles were analysed as well. From the measurements of the current harmonics it can be observed that the phase angles vary within a preferential range, i.e. remain within a range which is actually <90°of amplitude. These ranges can be translated into statistical distributions and be used into simulation inputs. Two of the Chargers failed to comply with the standards working individually Charger A barely makes it in terms of TDD and Charger C is out of the limit. In terms of individual harmonics also Charger A and Charger C are out of the limit of 4.5% for the 11th and 13th harmonics.

The next step of the research will be to obtain the statistical distribution of each of the phase angles for all Chargers and perform simulations with different scenarios. Among others, and to answer the research questions, the simulation stage will consider different configurations of Chargers (in number). The end goal is to evaluate the diversification of Chargers and if it reduces the THD_I due to the cancellation effect. Results so far suggest that stand alone Chargers with low short circuit values are recommended to have filters <13% THD. For multiple fast charging stations, the short circuit value should be sufficiently high so as to allow current harmonic values to be within standard limits.

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List of Abbreviations and definitions

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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Annexes

Annex A

Figures A1-A24 show the phase angle progression of phase L1 for all performed measurements for the 4 Chargers. The odd harmonic orders until the 13th are presented since they are the most significant ones. They all show preferential angle ranges enabling a statistical distribution identification and use in the simulation.

Charger A:

Figure A1 - Measurements of 3rd Harmonic Phase Angle from the Charger A

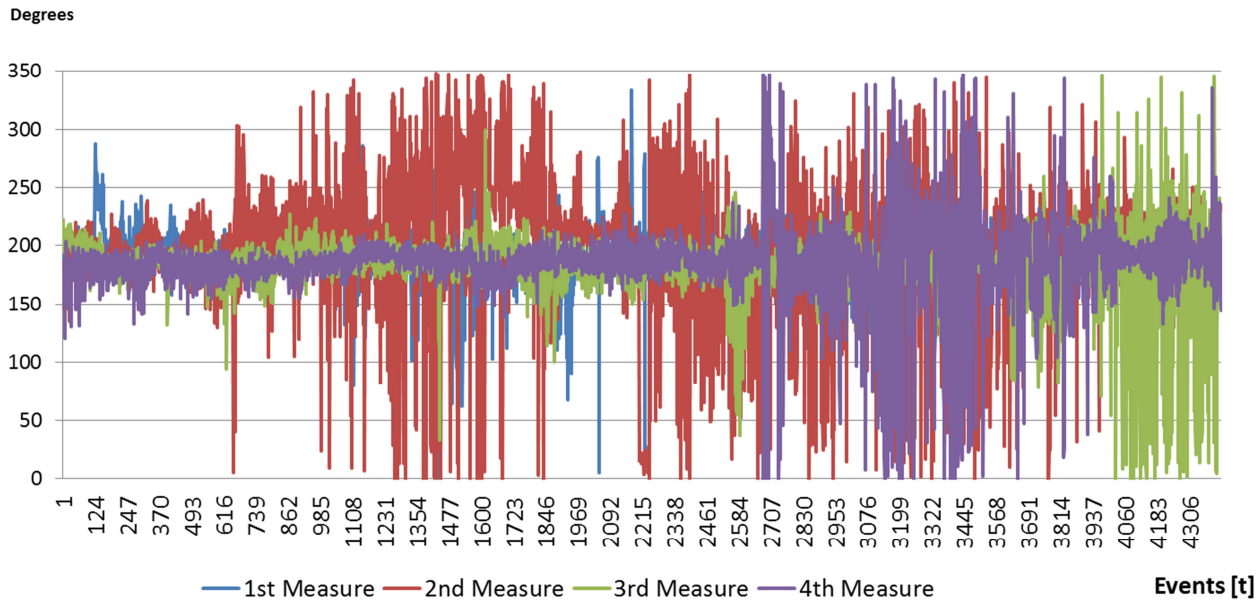


Figure A2 - Measurements of 5th Harmonic Phase Angle from the Charger A

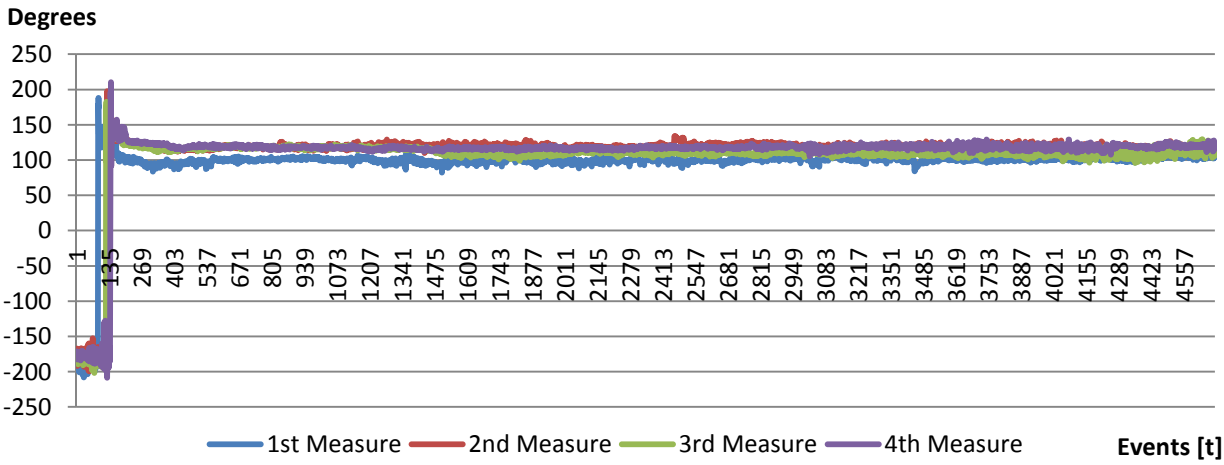


Figure A3 – Measurements of 7th Harmonic Phase Angle from the Charger A

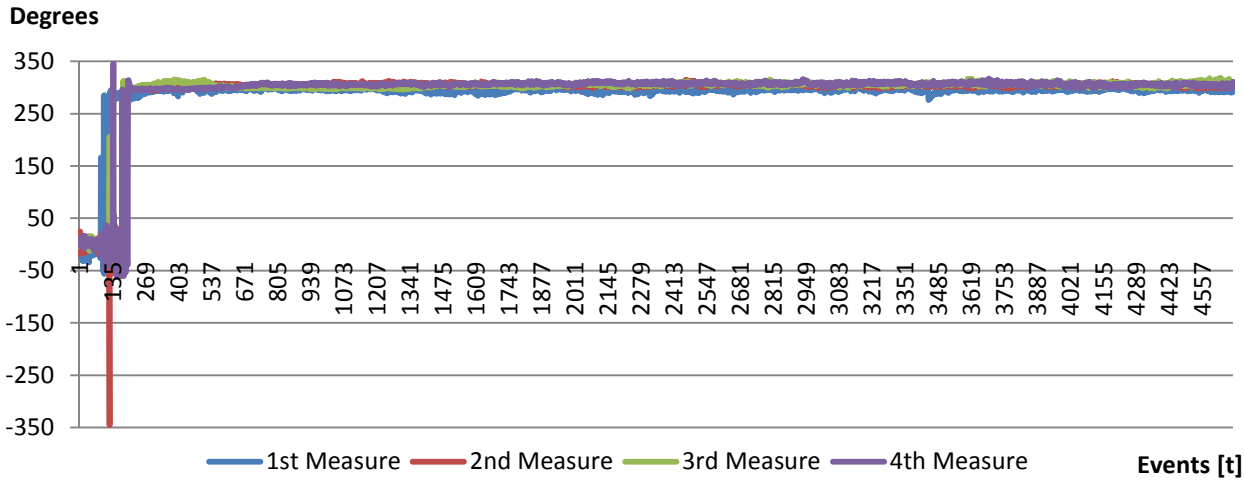


Figure A4 – Measurements of 9th Harmonic Phase Angle from the Charger A

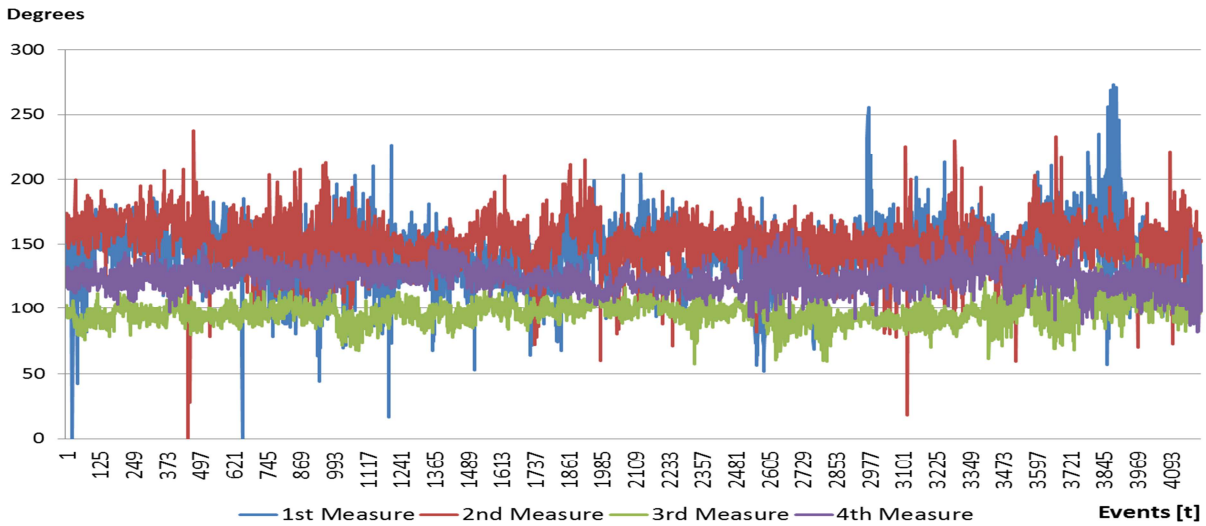


Figure A5 – Measurements of 11th Harmonic Phase Angle from the Charger A

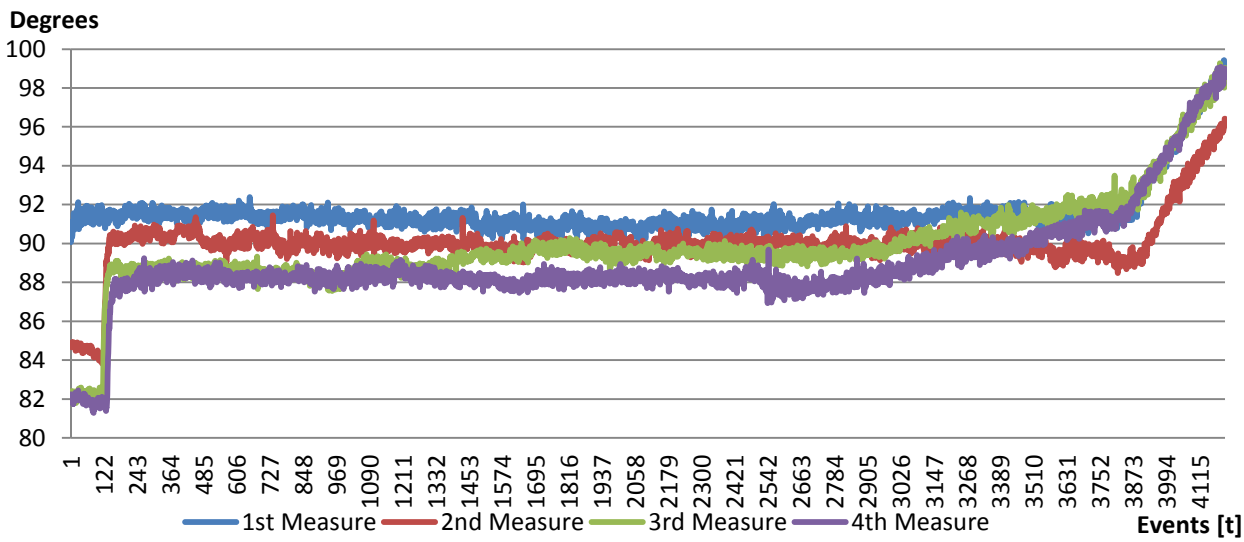
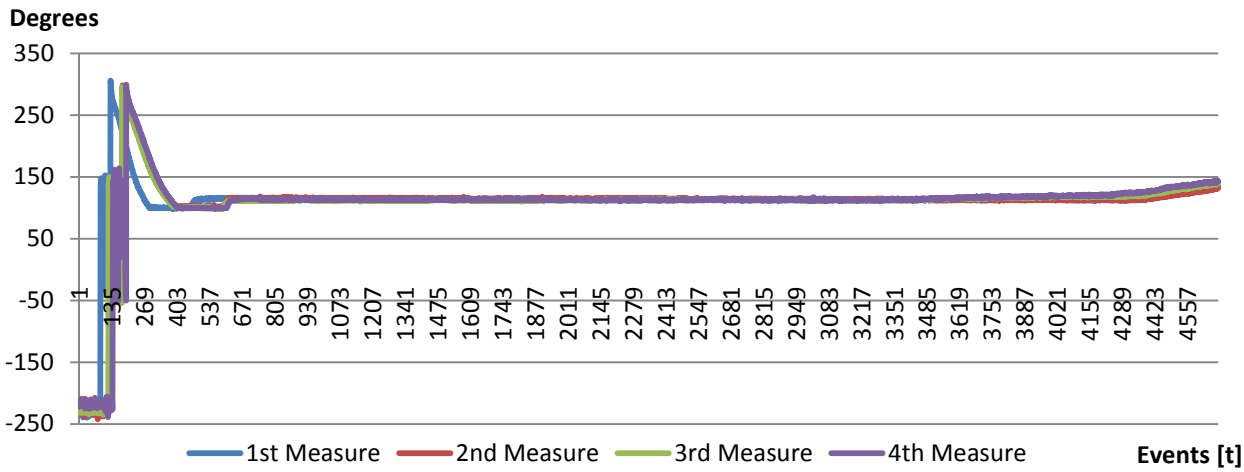


Figure A6 - Measurements of 13th Harmonic Phase Angle from the Charger A



Charger B:

Figure A7 - Measurements of 3rd Harmonic Phase Angle from the Charger B

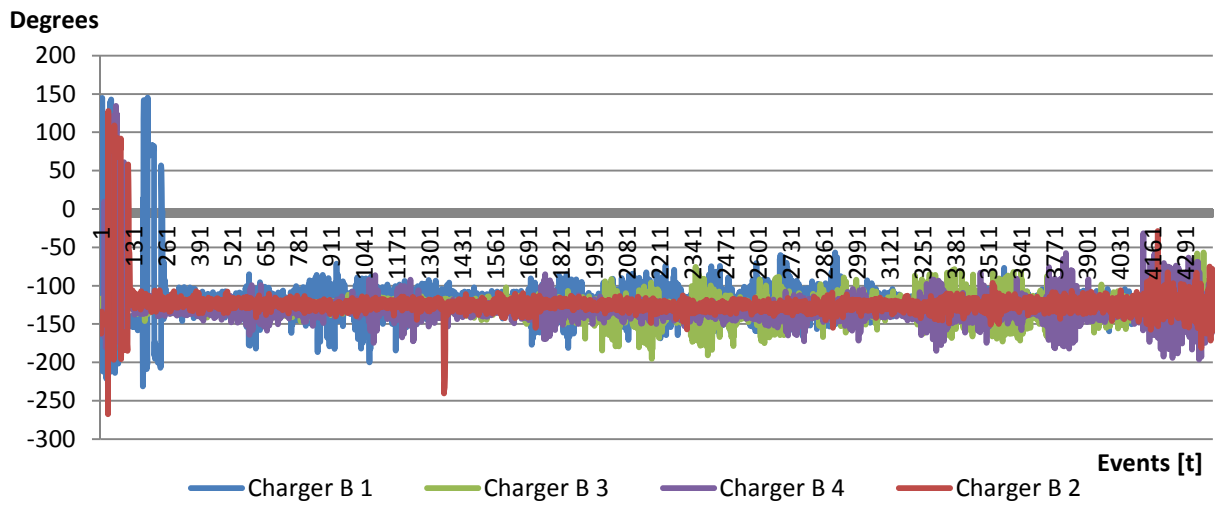


Figure A8 - Measurements of 5th Harmonic Phase Angle from the Charger B

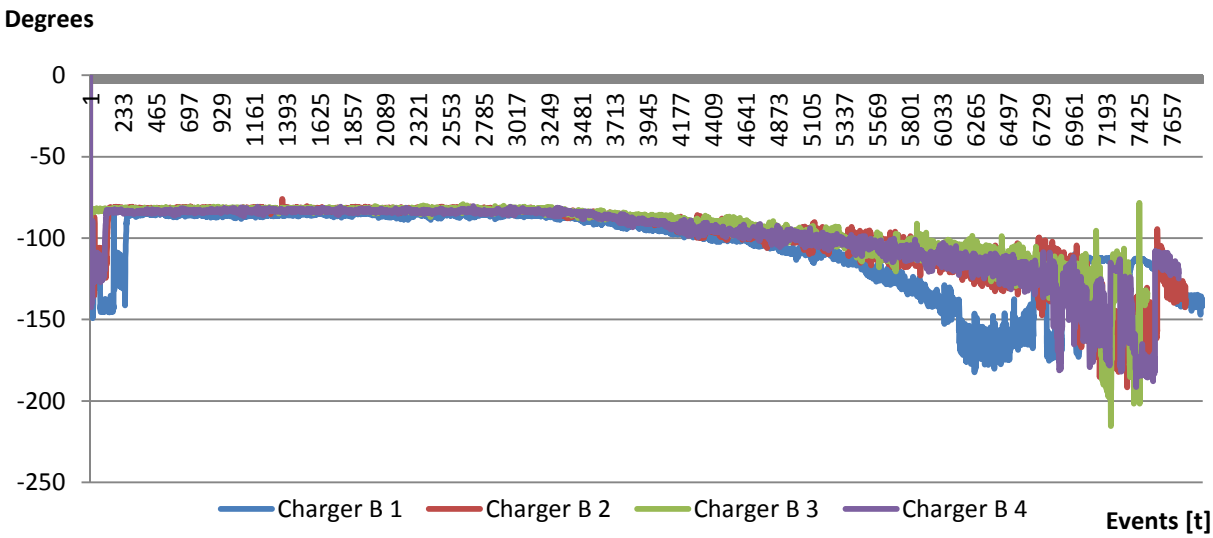


Figure A9 - Measurements of 7th Harmonic Phase Angle from the Charger B

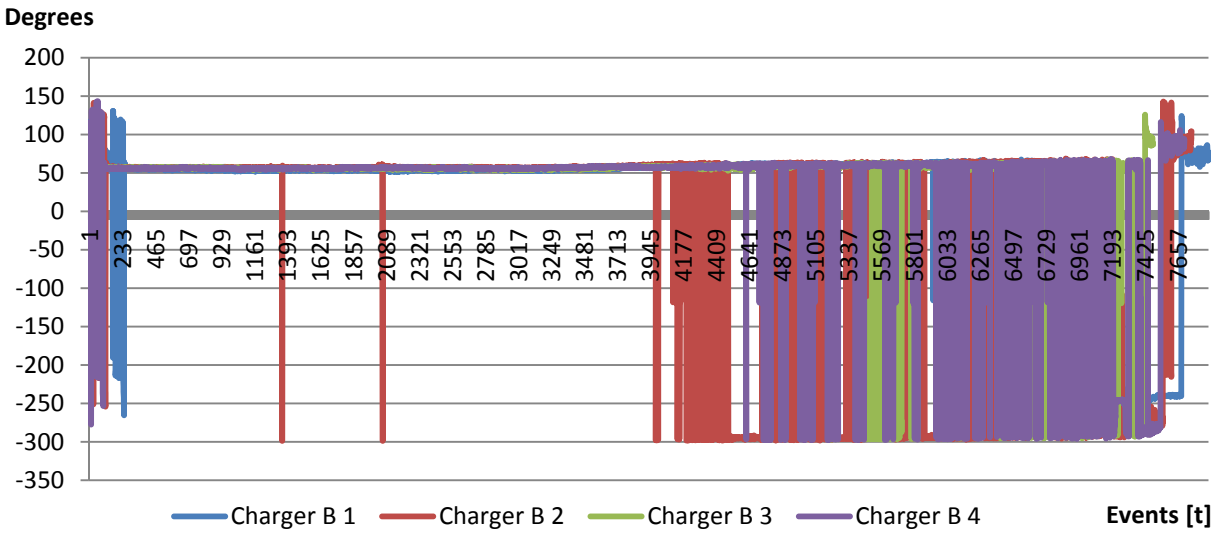


Figure A10 - Measurements of 9th Harmonic Phase Angle from the Charger B

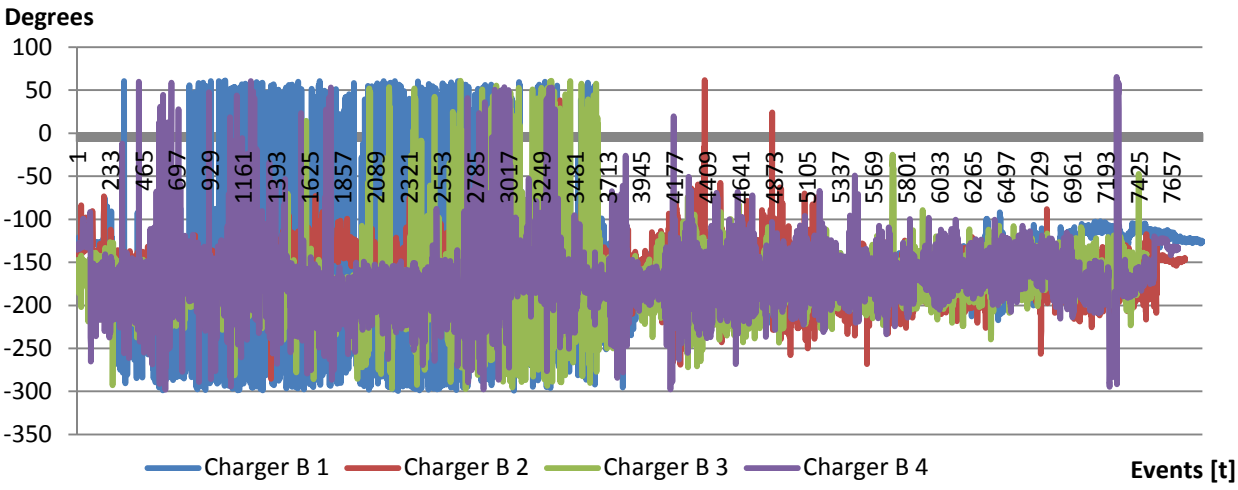


Figure A11 - Measurements of 11th Harmonic Phase Angle from the Charger B

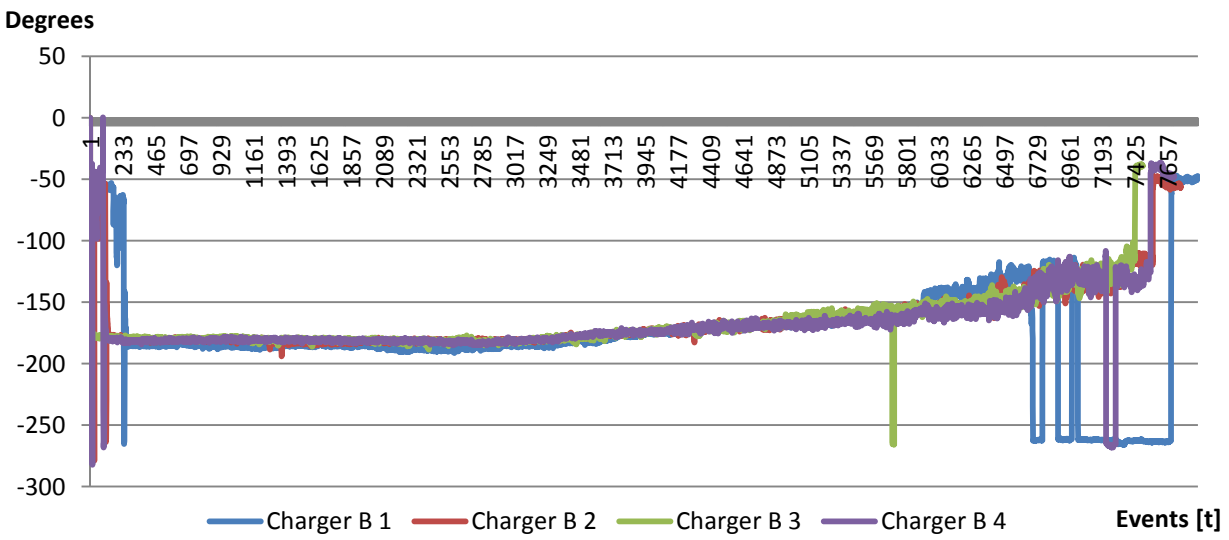
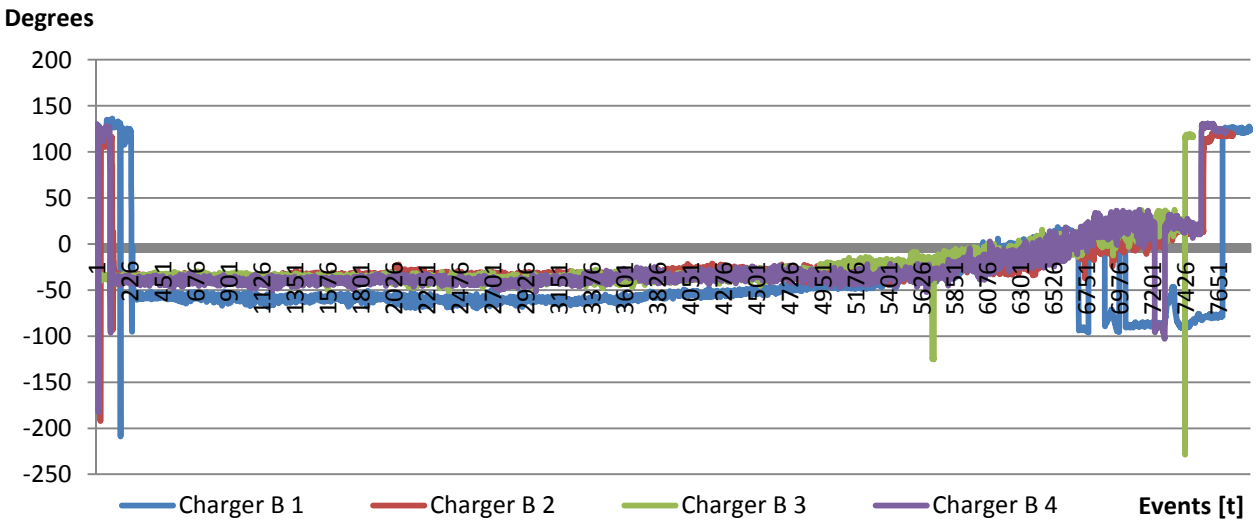


Figure A12 - Measurements of 13th Harmonic Phase Angle from the Charger B



Charger C:

Figure A13 – Measurements of 3rd Harmonic Phase Angle from the Charger C

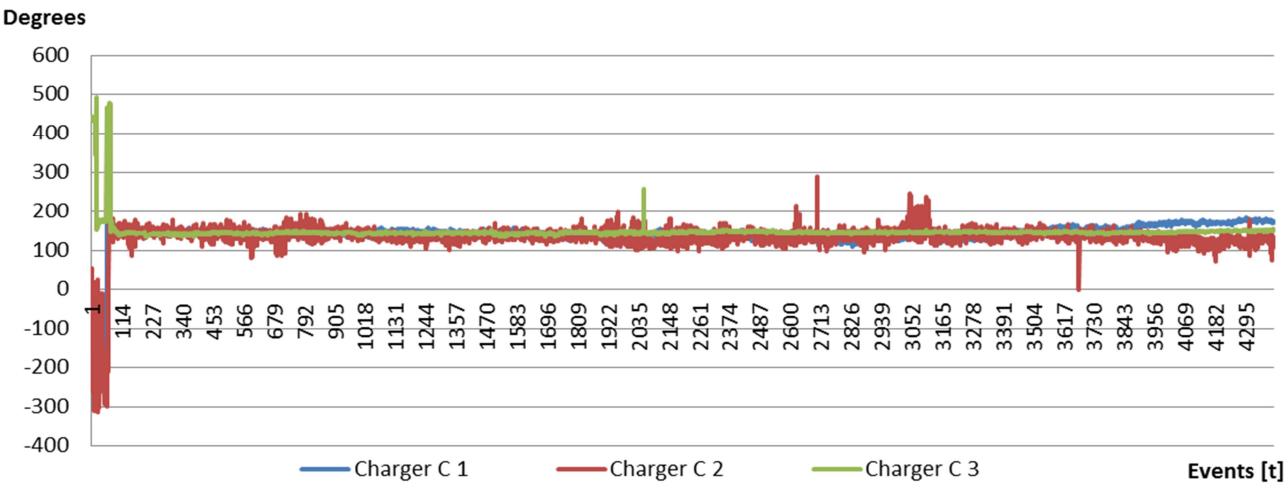


Figure A14 – Measurements of 5th Harmonic Phase Angle from the Charger C

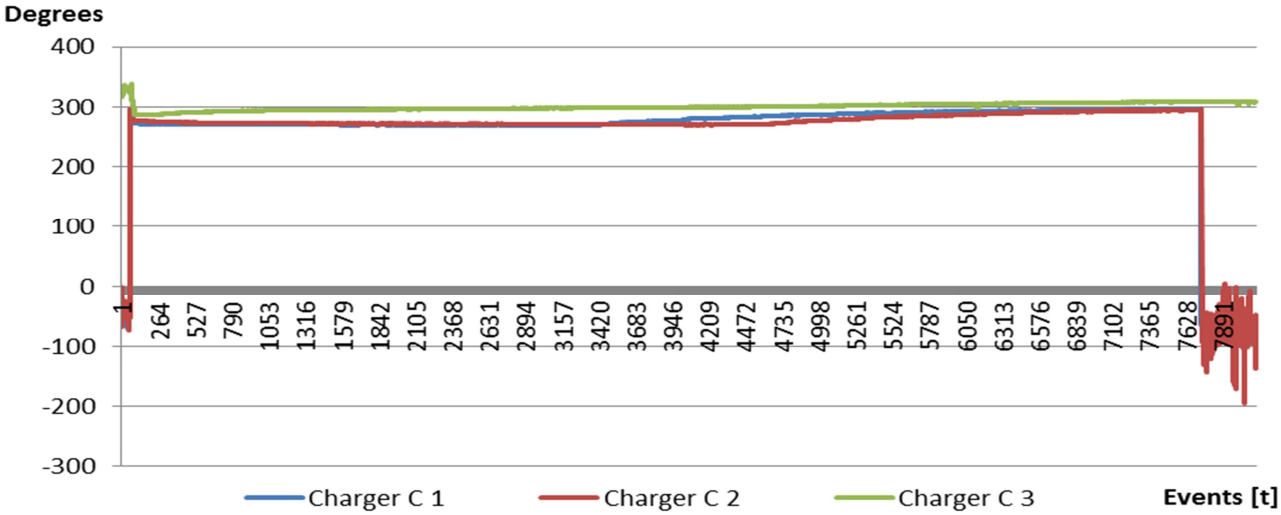


Figure A15 – Measurements of 7th Harmonic Phase Angle from the Charger C

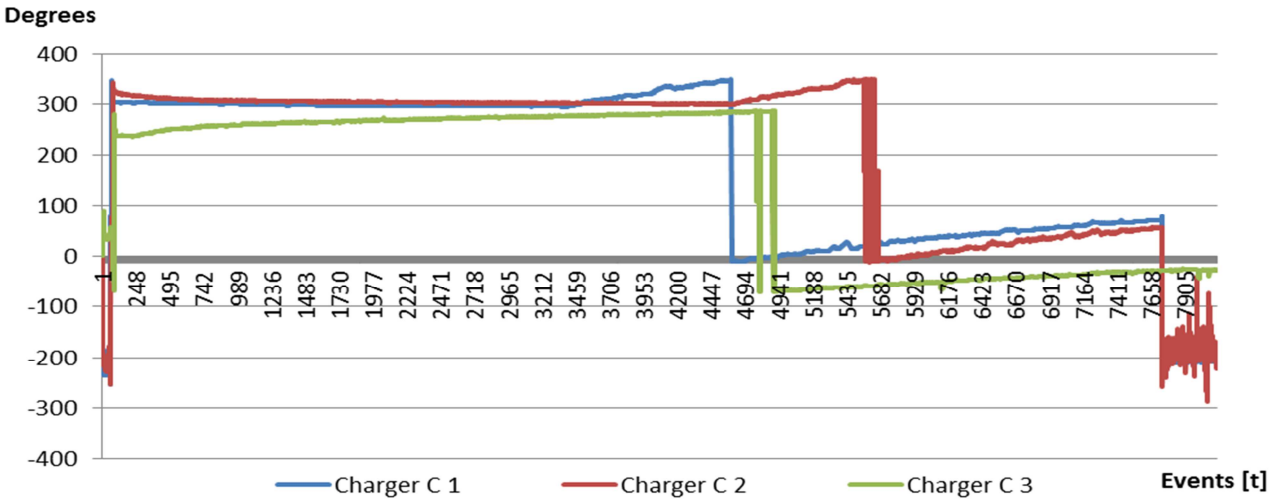


Figure A16 – Measurements of 9th Harmonic Phase Angle from the Charger C

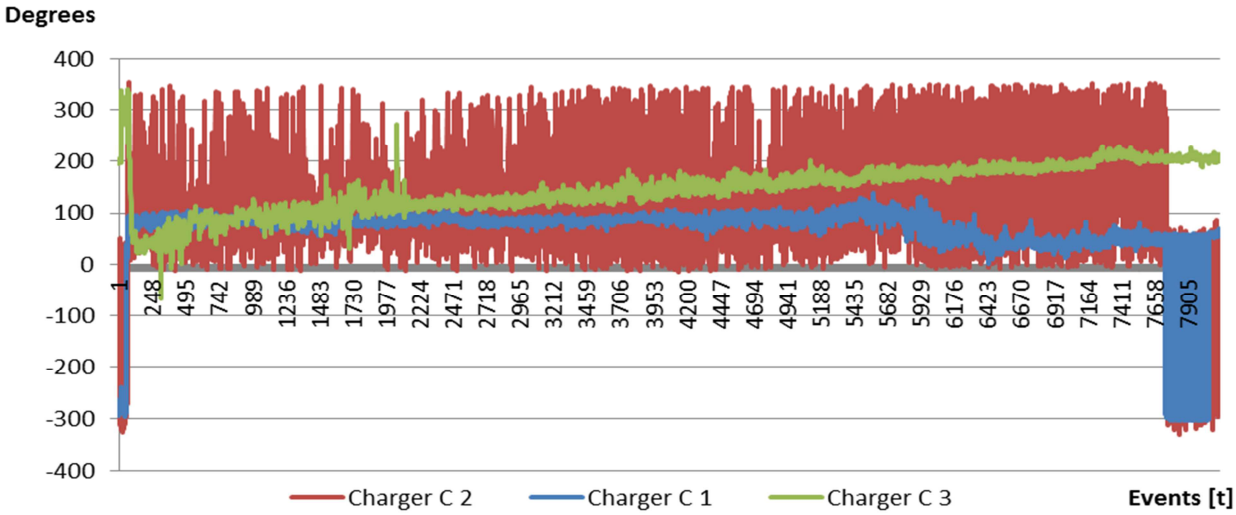


Figure A17 – Measurements of 11th Harmonic Phase Angle from the Charger C

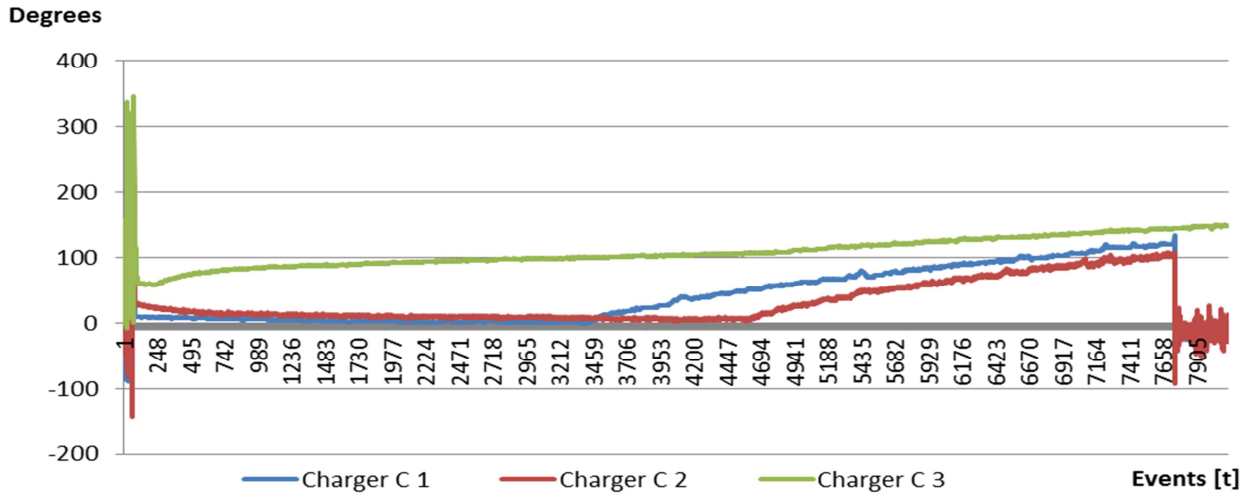
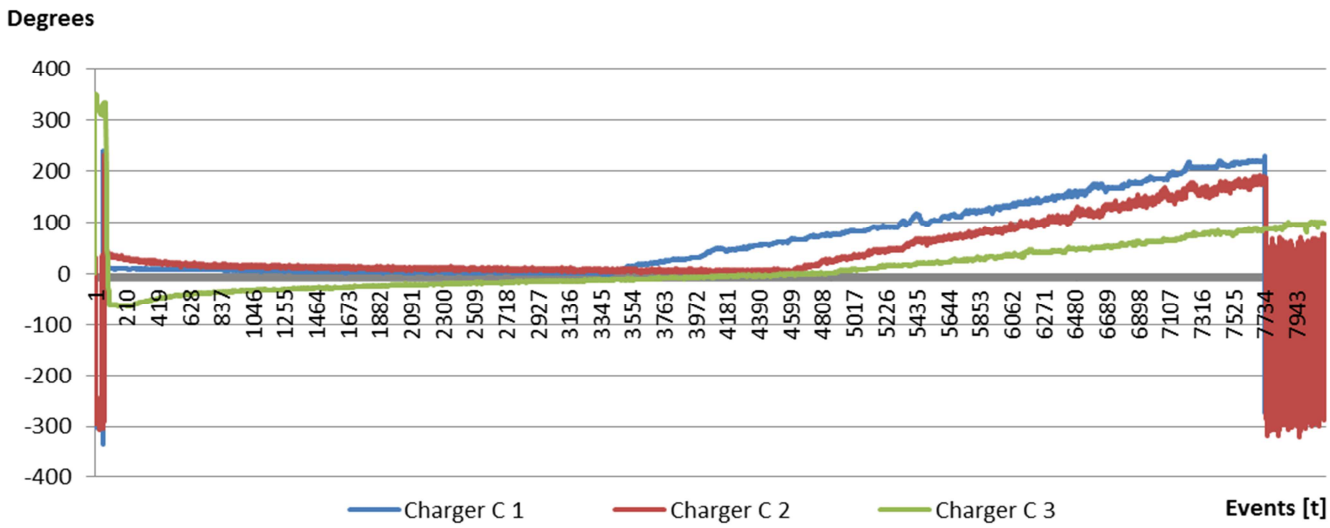


Figure A18 – Measurements of 13th Harmonic Phase Angle from the Charger C



Charger D:

Figure A19 - Measurements of 3rd Harmonic Phase Angle from the Charger D

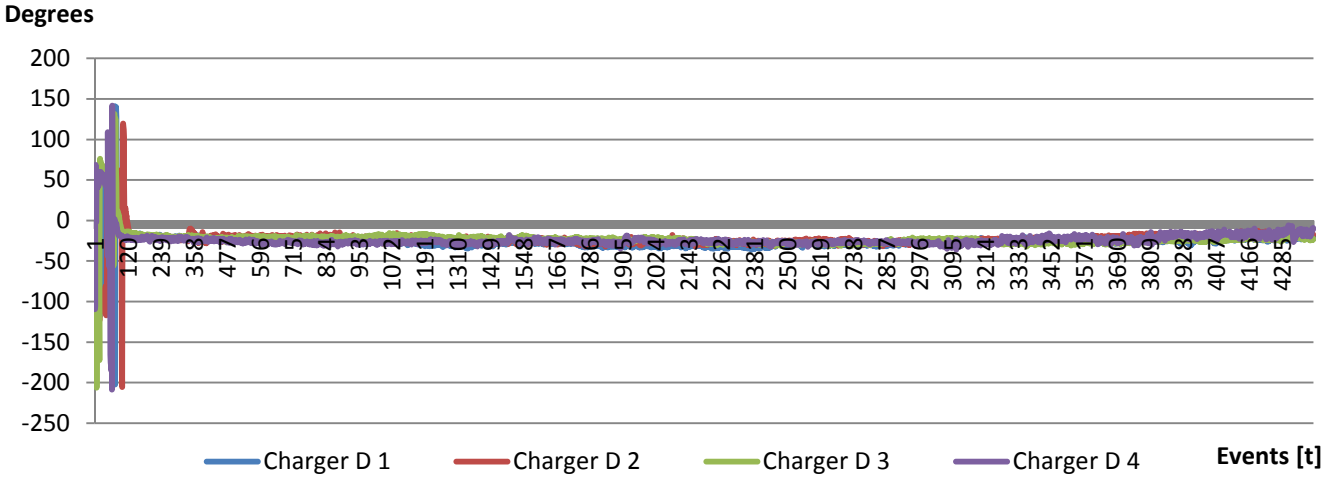


Figure A20 – Measurements of 5th Harmonic Phase Angle from the Charger D

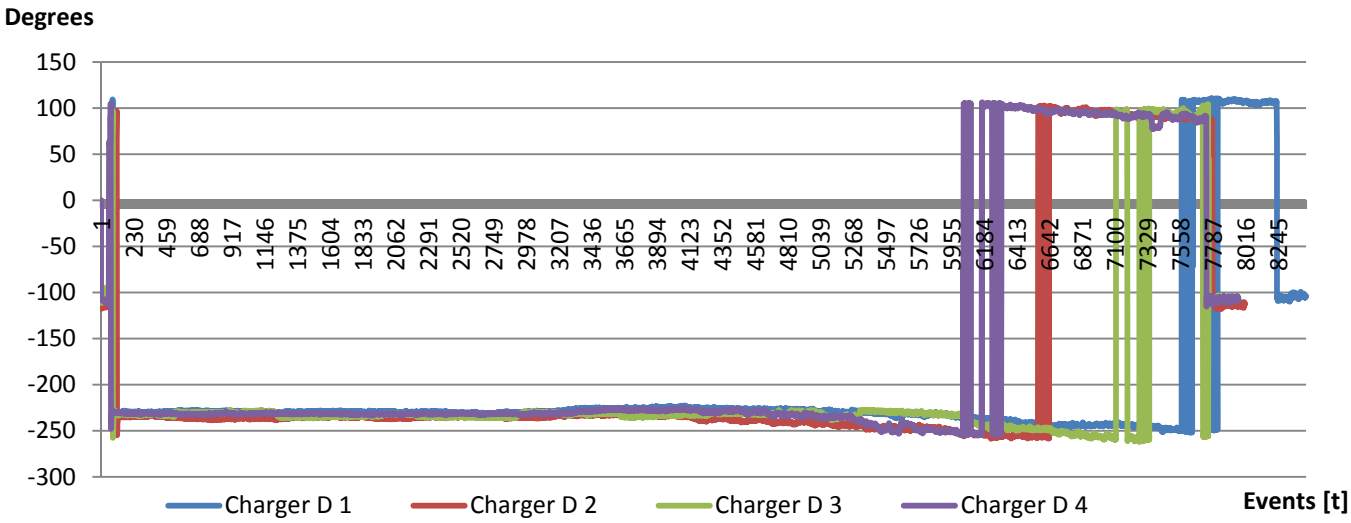


Figure A21 – Measurements of 7th Harmonic Phase Angle from the Charger D

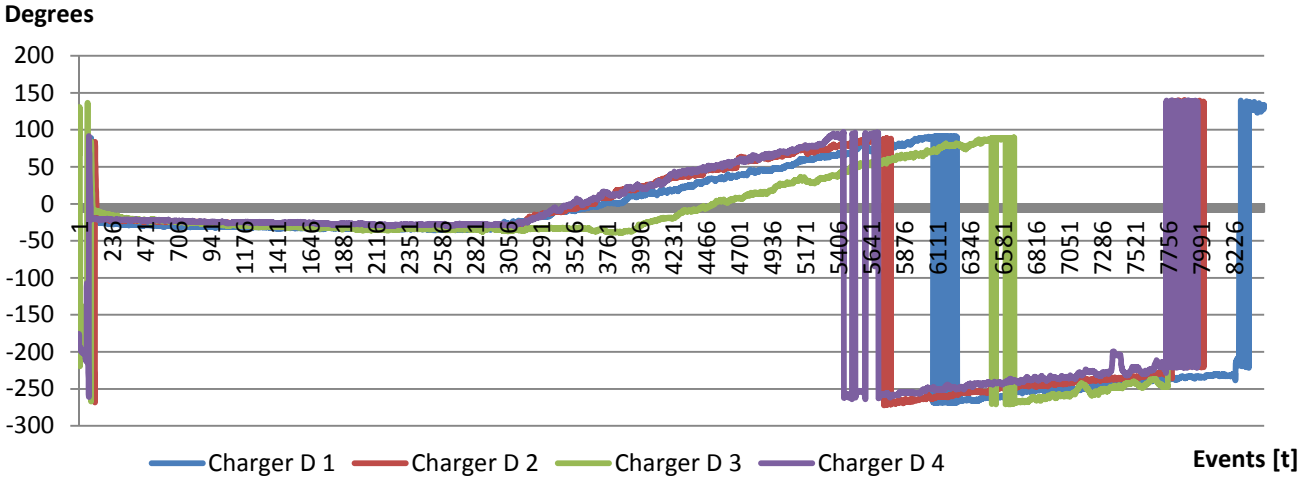


Figure A22 – Measurements of 9th Harmonic Phase Angle from the Charger D

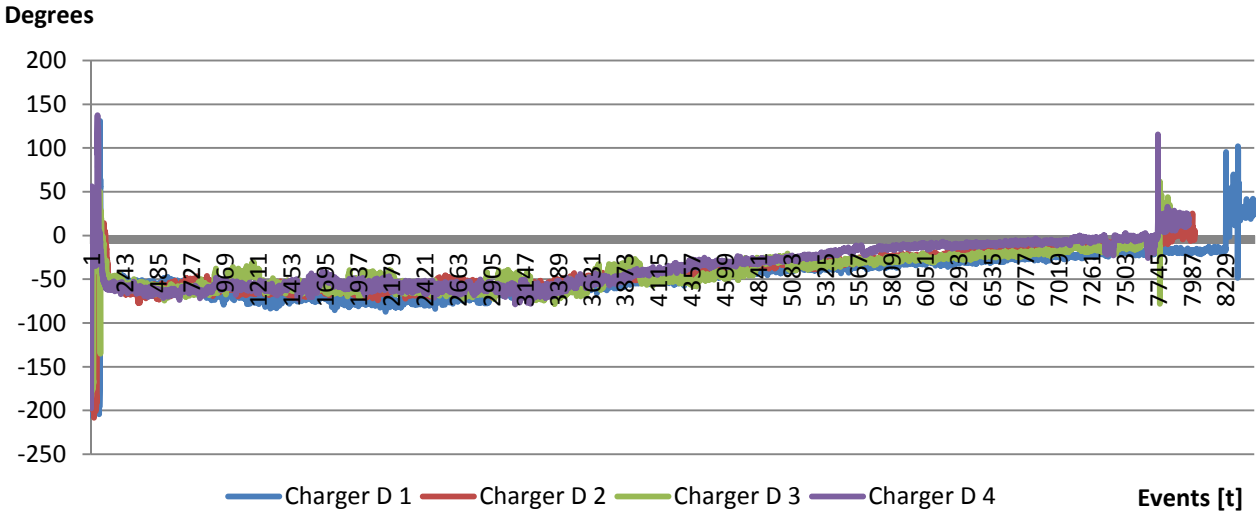


Figure A23 – Measurements of 11th Harmonic Phase Angle from the Charger D

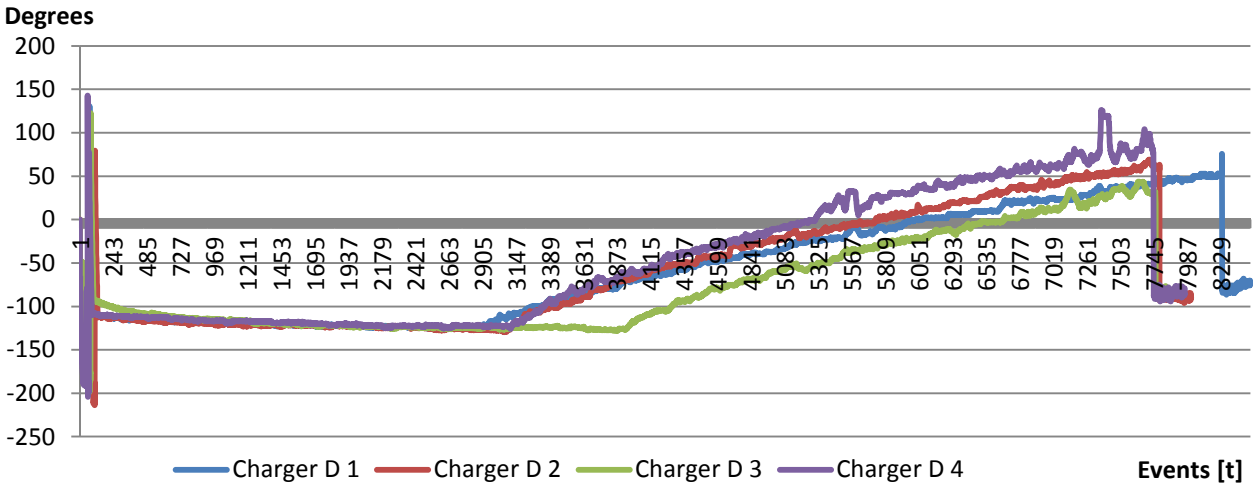
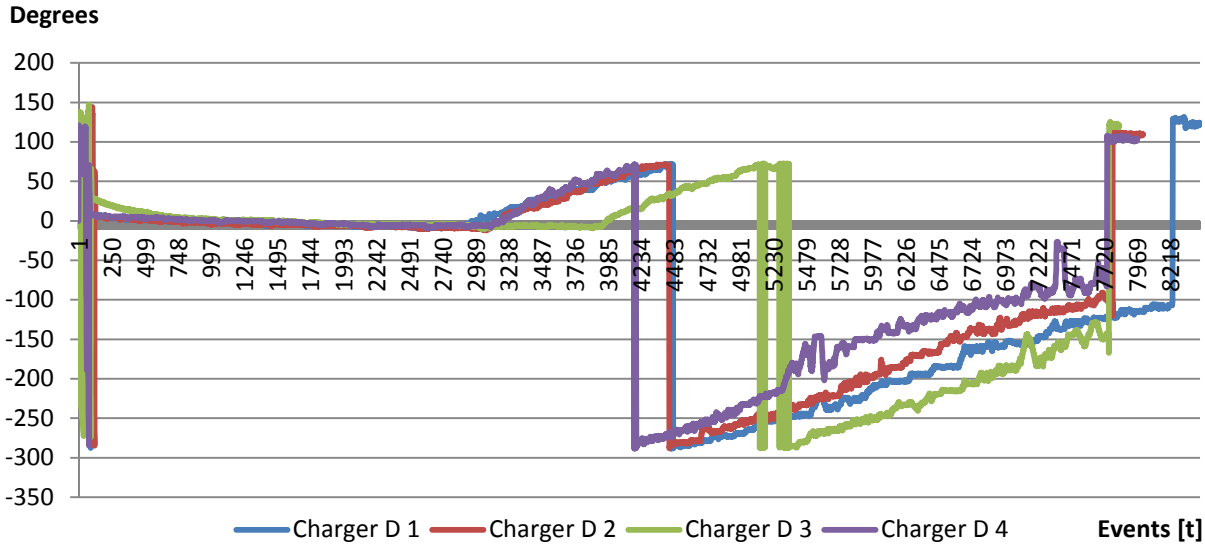


Figure A24 – Measurements of 13th Harmonic Phase Angle from the Charger D



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