Deliverable D4.3 – A1
Grid Impact studies of electric vehicles

EVs´ impact on Power Quality related to harmonics

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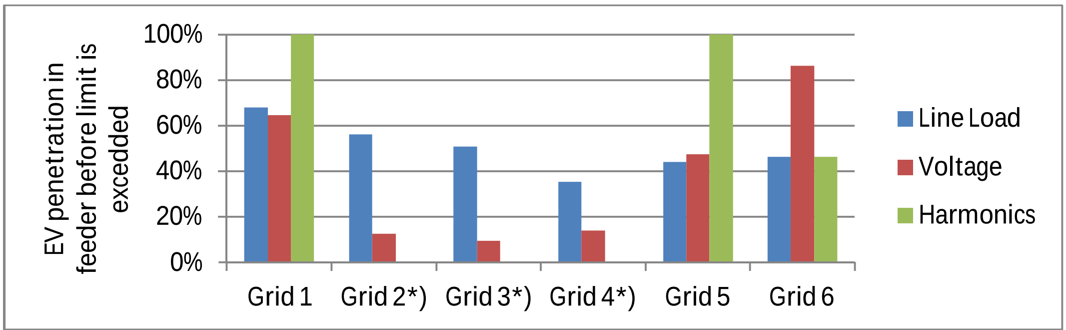
1 Executive summary

The scope of this report is to describe the impact of EVs related to harmonics, i.e. electric voltage and current that appear on the electric power system as a result of non-linear electric loads, with focus on low-voltage grids in households as primary consumption. The method has been chosen and developed in accordance with EV charging done in household installations and with focus on a charging level of 16 A at 230V.

Harmonic load flow simulations in Power Factory have been performed for three different charging strategies, User dependent, Timer Based and Load dependent. Based on a "base-case" simulation on 30 specific low-voltage grids from Italy, Spain and Denmark, 6 specific grids have been selected for a more comprehensive assessment.

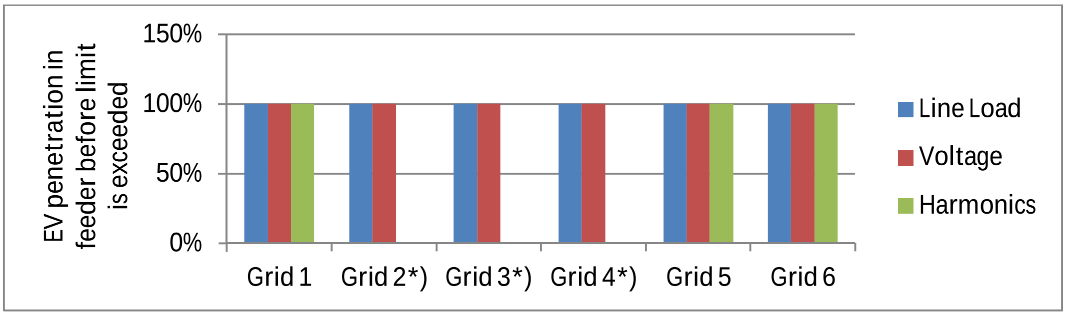
By adding one EV at a time to a grid, the maximum number of EVs to be connected to the grid was determined in terms of the voltage getting too low (Voltage), overload of the cables (Line Load) and electrical distortion of the supply voltage from power supplies and chargers etc. (Harmonics). The figure below gives an overview of the results.

User dependent charging



User dependent charging: EVs are charged when people returns from work, i.e. in the peak hours.
**) With no EVs the limit is exceed.*

Load dependent charging



Load dependent charging: EVs are charged in low load situation i.e. not in the peak hours
**) With no EVs the limit is exceed.*

In the load dependent charging, the charge power is modulated (reduced) to minimize the overall peak load. When the charge power is modulated, the distortion of the supply voltage is increased due to the behavior of the power electronics. Thus the relative harmonic emission per EV is higher in the load dependent charging scenario compared to the user dependent charging. However, the total level of harmonics is lower in the load dependent charging as the maximum total charge power is reduced and the charging takes place when the existing load is relatively low.

From the analysis, harmonic emissions from EVs are not expected to create a need for reinforcement of the grid in nearest future, but could be considered as a severe issue for communication like e.g. Power Line Communication. The results show that sufficient short-circuit level is the most important parameter to avoid harmonic distortion. This should be considered when extending or reinforcing the existing grid, as great improvements can be achieved with relatively low costs. Furthermore, the results show that the total level of harmonics is highly dependent on other types of equipment connected to the grid also.

Even though it is outside the scope of this assessment, it is to be mentioned that EVs cannot be assessed separately from other distorting equipment; thus the topic needs attention to develop the right standards and assessment methods.

A closer cooperation between manufactures and DSOs in the field of electromagnetic compatibility should be established in order to ensure compatibility between equipment connected to the public electricity grids.

Smart meters or any other sensor device, capable of measure harmonics, can play a key role in the future for integrating harmonics into the grid planning. A comprehensive collection of data regarding harmonics is very expensive due to the personal costs related to on-site measurements. An evolution of the already existing functionalities related to harmonics in today's smart meters, could provide the required data in order to include harmonics into future grid planning tools.

2 Introduction

Europe is undergoing a change from fossil based energy consumption to renewable energy sources such as wind, water, solar energy, burning of waste and bio products. A great part of this development has been in the electric market, exchanging the known power production units to something more environment friendly, thus reducing CO2 emission and lowering the dependency on heavy fuel oil products (HFO). For a likewise exchange in the transportation sector, the electric vehicles have long been in use as trams and trains. To fulfill the Transport roadmap 2050[1] which states a drastic reduction of CO2-emission from the transport sector, new technology is needed and for the ICE car the electric car is moving in.

2.1 Electric Vehicles for personal transportation

The exchange from oil based cars to electric cars (EVs) will have a significant and positive effect on society, local environment in particular and set new demands to the electric grid.

Despite Internal Combustion Engine Cars (ICE), EVs are connected to and uses the electric grid when refueling, either via an On-board charger or via an Off-board charger.

Chargers are in general connected to the low-voltage grid, and characterized by drawing a non-sinusoidal current. This characteristic leads to voltage distortions in the electric system. The degree of voltage distortions is depending on several parameters, both parameters related to the charger and parameters related to the grid.

To determine whether voltage distortions should be considered in planning and maintenance of low-voltage grid or not, several topics are outlined in the following.

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[1] A goal for the future in the transportation sector, details can be seen e.g. at: http://europa.eu/rapid/pressReleasesAction.do?reference=IP/11/372&format=HTML&

2.1.1 EU Project Green eMotion and D4.3

The large EU project Green eMotion focuses on electric vehicles; the technical development, penetration, and interaction with society. The project consists of eleven work packages investigating numerous topics related to EVs. The project is supported by partners throughout the European continent and each investigation stands as a small part of a larger picture.

D4.3 will include recommendations for future planning tools for DSOs and an investigation of the effect EVs have on the grid and power quality. D4.3 consists of several reports covering different topics relating EVs to the electrical grid. An overview of D4.3 is shown in Figure 2.1.1.

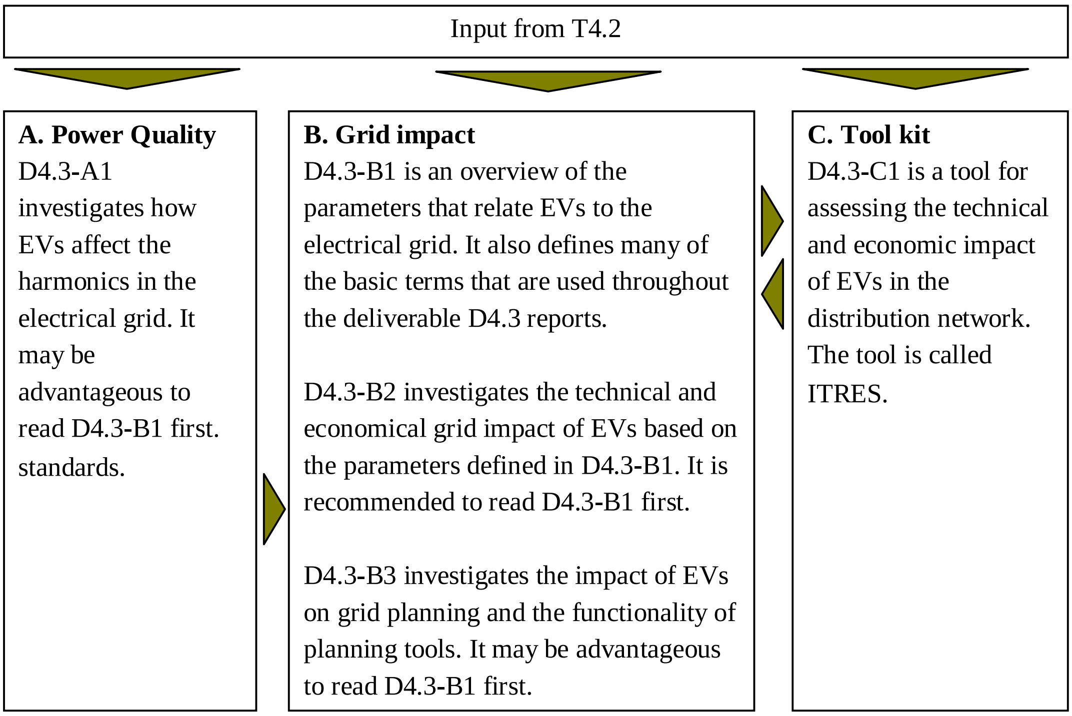

Figure 2.1.1: Overview of deliverable D4.3.

All reports are available on the Green Emotion website under following link: http://www.greenemotion-project.eu/dissemination/deliverables-infrastructure-solutions.php

2.1.2 The subject for the Investigation

In the following, the main subject for the investigations is EVs impact on the low-voltage grid in relation to harmonics due to a massive roll out of EVs. The investigations are focused on charging at private households as it is deemed important due to the number of charging facilities and a significant increase of power consumption at households.

The objective is to determine whether harmonics should be considered in grid planning and to give recommendations to future standardization work in the area of Harmonics. The investigations include:

- Comparison of IEC calculations and PowerFactory simulations
- Analysis of charging strategies influence on harmonics
- Analysis of grid topologies influence on harmonics

2.2 Outline of this report

In this introduction the GeM-project has been described underlining the aspects of this investigation and their relation to the entirety. The introduction chapter ends with the terminology in use in this report, including a table as common source of abbreviations, to aid the reading process.

Chapter 2 gives a review on harmonics, what is harmonics, what is the concerns regarding harmonics and which standards are relevant for assessing EVs impact on the grid in relation to harmonics.

Chapter 3 describes the methods used to perform the calculations and simulations covered by this report.

In Chapter 4 the results of the calculations and simulations are presented followed by further analysis of the results.

Chapter 5 perspectives on the results are performed including recommendations to further actions related to the topic of harmonics.

2.2.1 Terms and Abbreviations

The commonly used abbreviations and terms are shortly described below. Since the project is European, the terms are all relate to the general European standard.

Abbreviation	Representation	Explanation

DSO	Distribution System Operator, grid owners	The company which owns the lower voltage level grids. The company can be a private owned enterprise, state-owned or mixed.
IEC	International Electrotechnical Commission	International standardization organization that develop standards for markets worldwide. IEC in front of the number of a standard indicates that the standard is adopted by the International Electrotechnical Commission.
EN	European Norm	EN in front of the number of a standard indicates that the standard is adopted by the European Committee for Electrotechnical Standardization (CENELEC)
EV	Electric Vehicle	Electric car which recharges its battery from the grid. Substitute for an ordinary commuter family car, not a truck or a train.
EVSE	Electric Vehicle Supply Equipment	The charger or charger stand, including cables and electronics for communication.
PCC	Point of Common Connection	In general the point in a grid where a specific component is connected.
PQ	Power Quality	Describes the quality of a grid or in a point of the grid, by use of several parameters which can be measured or calculated.

Table 2.2.1 Abbreviations of importance.

3 Review on Harmonics

3.1 Description of Harmonics

During the last decades more electronic equipment is connected to the electric grid via residential installations, such as cooking plates, televisions, computers, LEDs etc., contains semi-conductor based switch mode converters. Likewise larger appliances, such as heat pumps, PV systems and EVs have become more common in residential installations over the past years. These types of equipment have one thing in common they do not draw a sinusoidal current from the electric grid. These types of loads are characterized as non-linear loads, and are denoted distorting loads or harmonic sources.

The current waveform of the non-linear loads can be characterized by a combination of a fundamental frequency, e.g. 50 Hz and a number of frequencies as a multiple of the fundamental frequency. Last-mentioned are denoted harmonic and interharmonic frequencies.

Harmonic frequencies are integral multiples of the fundamental supply frequency, i.e. for a fundamental of 50 Hz, the third harmonic would be 150 Hz and the fifth harmonic would be 250 Hz.

Any frequency which is a non-integer multiple of the fundamental frequency is denoted interharmonics. By analogy to the order of a harmonic, the order of interharmonic is given by the ratio of the interharmonic frequency to the fundamental frequency.

Harmonics and interharmonics of the current waveform lead to distortion of the voltage waveform, e.g. the fundamental frequency of the voltage waveform is superposed by frequencies as a multiple of the fundamental frequency – harmonics and interharmonics. The relation between the current waveform and the voltage waveform is the impedance in the electric grid at the frequency under consideration, e.g. the 5^{th} harmonics (250 Hz).

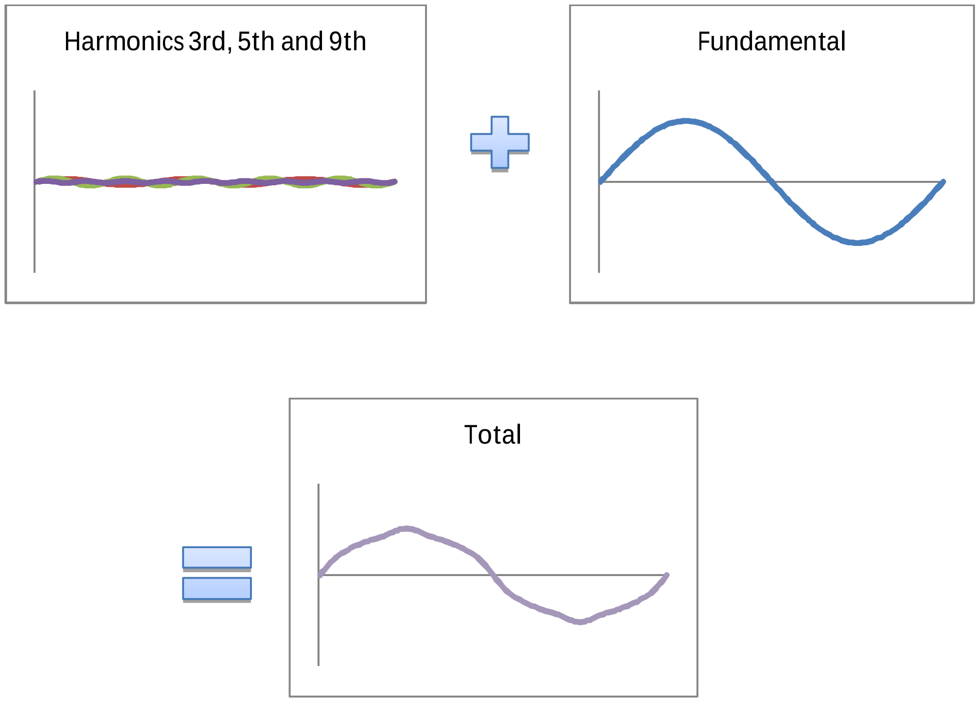

Figure 3.1.1 Harmonic distortion of fundamental waveform

3.2 Concerns regarding Harmonics

Distribution Network Operators (DNOs) across Europe are under obligation to deliver a certain quality of service to the producers and consumers connected to their grids. This service quality includes quality of supply (amount of power outage) and quality of the supply voltage, also denoted Power Quality.

The term Power Quality covers different elements, e.g. steady state voltage drop, rapid voltage drop, flicker and harmonics.

Steady state voltage drop, rapid voltage drop (caused by in-rush current of electric motors) and grid capacity are well known terms for grid planners and engineers working in the electricity industry, and have been used as design criteria for low-voltage grids and low-voltage installations for years.

Other elements such as flicker and harmonics are not considered in relation to the design of low-voltage grids and low-voltage installations. Those elements are typically considered in relation to product design, where the acceptable emission limits and minimum immunity requirements are specified in international standards. The acceptable emission limits given in the standards are based on various assumptions, e.g. the electricity system to which the equipment is to be connected, and the amount of equipment with non-linear characteristics.

The prevalence of non-linear loads i.e. EVs and production units, connected to the low-voltage grid, may very well have an influence on the validity of the assumptions on which the emission standards are based. Seen from a grid perspective, EVs are relatively large appliances in terms of energy consumption, compared to other residential appliances.

A massive roll out of EVs is from a DNO's perspective, connection of a large number of distorting energy consuming loads. The question is if a massive roll out of EVs is a reality, will DNO's obligations regarding Power Quality then be maintained? Does the fact that EVs are distorting loads make Harmonics an element to consider when designing or reinforcing grids?

3.3 Relevant Standards

Within the European Union, requirements regarding harmonics are regulated by the EU directive on Electromagnetic Compatibility 2004/108/EC. In short, the directive states that one apparatus should not disturb another apparatus in a way that could compromise its operation as intended. Opposite one apparatus should be designed to operate without unacceptable degradation of its intended use in the environment in which the apparatus is intended to be used in. The EU directive is not particularly operational, as the directive only includes essential requirements and not specific values for maximum acceptable emission levels and minimum immunity levels. As mentioned previously, emission and immunity levels are specified in international standards. The most relevant standards concerning harmonics are the following standards:

IEC/EN 61000-2-2:2002 *Electromagnetic compatibility (EMC) - Part 2-2: Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems*

This Standard specifies compatibility levels at the point of common coupling. The compatibility levels specified in this standard are used as reference levels for co-ordination in the setting of emission and immunity limits for equipment or installations connected to the public low-voltage electric grid. Compatibility levels are generally based on the 95 % probability levels of entire systems, using distributions which represent both time and space variations of disturbances.

There is allowance for the fact that the system operator cannot control all points of a system at all times. Therefore, evaluation with respect to compatibility levels should be made on a system-wide basis and no assessment method is provided for evaluation at a specific location.

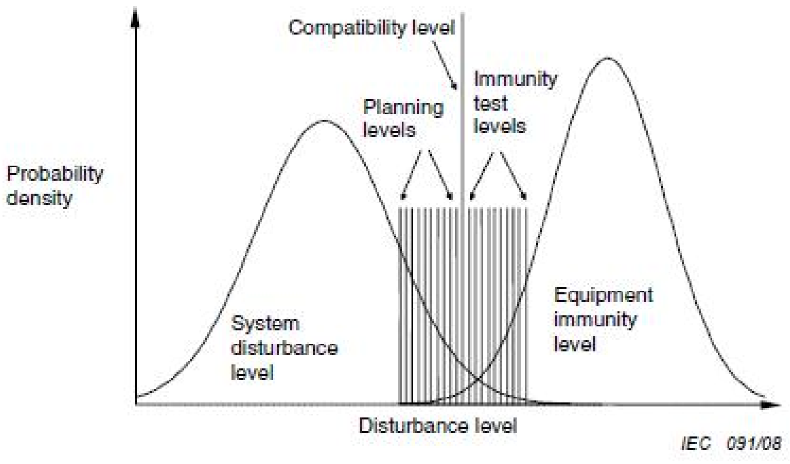

Figure 3.3.1 System disturbance level and equipment immunity level

Figure 3.3.1 shows the relation between System disturbance level and the equipment immunity level. As long as the actual Disturbance level of the system is lower than the actual immunity level of the equipment connected to the system, the equipment will operate as intended.

EN 50160:2010 *Voltage characteristics of electricity supplied by public electricity networks*

This European Standard specifies the main characteristics of the voltage at a network user's supply terminals in public low-voltage, medium and high-voltage electricity networks under normal operating conditions. This standard describes the limits or values within which the voltage characteristics can be expected to remain at any supply terminal in public European electricity networks, and does not describe the average situation usually experienced by an individual network user. DSOs across Europe refer to this standard in terms of accessing power quality and to verify that their obligations related to power quality are met. The harmonic voltage limits specified in this European standard are very similar to the compatibility levels given in IEC 61000-2-2, but the criterion used to assess the harmonic levels in EN 50160 is far more severe than the criterion corresponding to the definition of compatibility levels in IEC 61000-2-2[2].

To make system disturbance level meet the compatibility level and thus ensure that equipment connected to the grid can operate satisfactorily together, the equipment needs to fulfill certain requirements. The requirements are specified in either generic standards, product family standards or product specific standards and specified in a way that enables the manufactures to test for compliance. The generic standards are used where no product specific standards are available. Following two product family standards related to harmonics are relevant for EVs:

IEC/EN 61000-3-2:2009 *Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current <= 16 A per phase)*

This standard covers EVs charging at maximum 16 A per phase. Typical charging levels at residentials are covered by this standard. 16 A per phase corresponds to 3.7 kW single phase and 11 kW three phase at 230 V.

IEC/EN 61000-3-12:2011 *Electromagnetic compatibility (EMC) - Part 3-12: Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and <= 75 A per phase*

This standard covers charging levels up to 51.8 kW three phase at 230 V. Thus charging spots, which are commonly used for public and semipublic, are covered by this standard as the commonly rated power of those charging spots are 50 kW or less.

As well as standards have been developed for harmonic emission limits for equipment, a standard for immunity has also been developed. For EVs the following standard is relevant:

IEC 61000-4-13:2002 *Electromagnetic compatibility (EMC) - Part 4-13: Testing and measurement techniques - Harmonics and interharmonics including mains signalling at a.c. power port, low frequency immunity tests*

[2] Harmonic level measurements on French low-voltage networks, CIRED' 2007.

This basic standard covers charging levels up to 3.68 kW. Immunity test method for higher power ratings still needs to be considered.

With respect to emissions from large installations connected to public low-voltage power systems, the following technical report gives guidance to system operators:

IEC/TR 61000-3-14 *Electromagnetic compatibility (EMC) - Part 3-14: Assessment of emission limits for harmonics, inter-harmonics, voltage fluctuations and unbalance for the connection of disturbing installations to LV power systems*

This technical report provides guidance on the principles that can be used as the basis for determining the requirements for the connection of large disturbing installations to low-voltage public power systems. In addressing installations, this report is not intended for replacing equipment standards for emission limits.
The procedure is divided into three stages:

<u>Stage 1: Simplified evaluation of disturbance emission</u>
In general small appliances can be installed and connected to the grid without a specific evaluation of harmonics by the DSO. This is typically the case where the manufactures have designed equipment in compliance with EN61000-3-2 or IEC/EN61000-3-12. This means that chargers for residentials (on-board chargers), semipublic and public charging spots are not specifically evaluated by the DSO.

<u>Stage 2: Emission limits relative to actual system characteristics</u>
If the installation does not meet the criteria of stage 1 evaluation, the harmonic distorting equipment must be evaluated together with the absorption capacity of the electric grid. Related to EVs this is only relevant for fast charging with power ratings greater than 51.8 kW or dedicated charging stations with multiple chargers.

<u>Stage 3: Acceptance of higher emission levels on a conditional basis</u>
Where the installation does not fulfill the basic limits in stage 2, the customer and the DSO may agree on higher levels of emissions than the basic limits in stage 2. However, a comprehensive study of actual and future system characteristics must be carried out in order to ensure that the DSOs meet their obligations to other customers. As for stage 2, this is only relevant for fast charging with power ratings greater than 51.8 kW and dedicated charging stations.

As stated previously, this technical specification is not applicable to determine emission requirements to specific equipment; however, it can be used to determine the maximum global emission contribution of EVs, and to determine emission limits to large installations containing EVSEs, e.g. large charging stations.

In the previous report prepared by D4.3-B1 “Grid Impact studies of electric vehicles_Parameters for Assessment of EVs Impact on LV Grid” several parameters are identified, which are to be considered when performing a comprehensive assessment of EVs impact on electric low-voltage grid. One of those parameters is Power Quality -a set of parameters (harmonics, voltage, flicker) that describes the state of the grid and the likelihood of certain types of failure. The results of a comprehensive assessment of EVs impact on harmonic distortion in the low-voltage grid is presented in this report, taking into account the influence of other parameters identified. Following parameters have been considered in the assessment:

Grid Topology
The setup and components of the grid including size
A variety of specific low-voltage grids in terms of design, length, rural and urban areas and number of customers connected to the grid is used as basis for the assessment. However, the assessment is limited to low-voltage grids supplying residential areas.

Number of EVs
The number of EVs either on a radial, in a grid or in a country
The number of EVs have a significant impact on the level of harmonics in a specific grid as each individual EV contributes to the total level of harmonics. All grids have been assessed for penetration rates from 0-100 % EVs, corresponding to one EV per household.

Charging profile
A charging profile for a number of EVs: typically a curve depicting demand per hour or 15 minutes during a day.
The number of EVs which can be connected to the electric grid depends on the charging profile. Thus the level of harmonics depends on the charging profile, as level of harmonics are affected by the number of EVs. Three different charging profiles have been assessed. More details on the charging profiles can be found in annex 2 in “D4.3 Parameters for Assessment of EVs impact on Low-voltage Grid”

Charge ManaGeMent Strategy
The strategy or philosophy of how the charge of many EVs should be done in order to minimize negative effects on the grid
The Charge ManaGeMent Strategy has been indirectly assessed by changing the assessment of different charging profiles. More details on Charge ManaGeMent Strategies can be found in "D4.2 Recommendation on grid-supporting opportunities of EVs"[3]

Consumption
The general consumption of electricity at a given time, often expressed as hourly values during a day.
Most of the assessments are performed considering both the consumption of EVs and the traditional consumptions. This is done in order to determine whether the number of EVs to be connected is limited by harmonics or other parameters such as capacity.

Capacity
The capacity of a grid varies with the size the components and the level of voltage, current etc.
The grid capacity is considered in most of the assessments, as the number of EVs to be connected is limited by the capacity of the grid or due to harmonics. The capacity has been considered in both balanced connection of EVs and unbalanced connection of EVs. The last mentioned is relevant in case of single phase connections, which is common practice today.

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[3] Available on Green Emotion website under following link: http://www.greenemotion-project.eu/dissemination/deliverables-infrastructure-solutions.php

4 Harmonic Calculations and Simulations

4.1 Basis for calculations and simulations

4.1.1 Grids

The grids under examination in this report, are choosen to be very different grid examples, the only thing in common for each grid under investigation, is the fact that the grids consist of ordinary households only, thereby none of the grids are polluted by major industry etc.
The grids under the loop are from three different countries, more precisely Denmark, Spain and Italy. Furthermore, the grids differentiate from each other in a great many other parameters; number of consumers, the age of the grid etc.
By investigating such a variety of different grids, a broader perspective on the results is achieved, and thus gives a more reliable answer to the investigated problems.

4.2 IEC Guidelines

The International Electrotechnical Commission – IEC has provided a set of guidelines to determine the requirements for connection of large distorting installations to the public low-voltage electric grid. Guidelines related to harmonics are described in:

IEC/TR 61000-3-14 *Electromagnetic compatibility (EMC) - Part 3-14: Assessment of emission limits for harmonics, interharmonics, voltage fluctuations and unbalance for the connection of disturbing installations to LV power systems*

In most of the European countries, some of the calculations methods described in the above mentioned guidelines are used as basis for assessing distorting installations, however, mostly for production units. The assessments are typically carried out in a manual process, e.g. by using a calculator or an EXCEL spread sheet. Simulations tools, such as Digsilent Power Factory, already provide features to assess harmonics; however, the assessment of distorting installations in low-voltage grids are typically carried out manually, as low-voltage grids are not integrated into the simulations tools.

Despite the fact that the IEC guidelines are not intended for assessment purposes on impact from specific equipment the calculation methods described in the IEC guidelines are used as a basis for determing the global emission limits from EVs and the global contribution from EVs. A comprehensive assessment with a large number of loads according to the guidelines is very time consuming, why the calculations have been simplified by applying an average impedance.

4.2.1 Method of calculation

As mentioned in section 3.3 the IEC guidelines IEC/TS 61000-3-14 uses three stages of evaluation. The basis of the calculation method is stage 2 where the harmonic distorting equipment must be evaluated together with the absorption capacity of the electric grid. However, the calculations are simplified compared to the guidelines, in order to enable a manual process. The method is described in the following.

The starting point is to define the overall acceptable level for each harmonic, including both existing load and EV load. For this purpose the compatibility levels of low-voltage grids presented in the guidelines is used.

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,4	6	0,5
13	3	21	0,3	8	0,5
$17 \leq h \leq 49$	$2{,}27 \cdot \frac{17}{h} - 0{,}27$	$21 < h \leq 45$	0,2	$10 \leq h \leq 50$	$0{,}25 \cdot \frac{10}{h} + 0{,}25$
NOTE The compatibility level for the total harmonic distortion is THD = 8 %.					

Table 4.2.1 Compability levels in low-voltage grids

According to the technical specification, a relatively high share of approximately 75% of the overall acceptable level for each harmonic is reserved for the contribution from the upstream voltage level. This means that only 25% is reserved for the contributions from appliances connected to the low-voltage grid.

Only part of the total level of harmonics can be reserved for EVs, as the existing loads need its share too. The share to be reserved for EVs is calculated from following formula:

$$G_{hEV} = G_{hLV} \cdot \sqrt[\alpha]{\frac{S_{EV}}{S_{trf}}}$$

Where: G_{hEV} = Maximum contribution to the h^th harmonic voltage from EVs.

G_{hEV} = Maximum contribution to the h^th harmonic voltage anywhere in the low-voltage system .

S_{EV} = Nominel apparent power for the total amount of EVs connected to the grid.

S_{trf} = Nominel apparent power of the low-voltage transformer.

α = Summation exponent

Harmonic order	α (alfa)
$h < 5$	1
$5 \leq h \leq 10$	1,4
$h > 10$	2

The contribution from each individual EV is characterized by a harmonic current $I_{h,i}$ of each harmonic order *h*. The harmonic current of harmonic order *h* for the total number of EVs connected to the low-voltage grid I_h is determined by the following formula:

$$I_h = \sqrt[\alpha]{\sum_{i=1}^{N_{ev}} I_{h,i}^{\alpha}}$$

Where: I_h = Harmonic current of harmonic order *h* for the total number of EVs.

$I_{h,I}$ = Harmonic current of harmonic order *h* for individual EV *i*.

N_{ev} = Total number of EVs connected to the grid

α = summation exponent

To determine the harmonic currents contribution to the voltage harmonic, the impedance of the grid at the frequency corresponding to the harmonic order under consideration, is determined. For this purpose, an average resistance at 50 Hz and reactance is determined for each grid. This is done by calculating the average impedance of each node in the grid. The frequency dependency is characterized by following formula:

$$Z_h = R_{50Hz} + \frac{f}{50} X_{50Hz}$$

The prerequisite of the scenario is that emission from each EV corresponds to the emission limits specified in EN61000-3-2.

4.3 Simulations in Digsilent Power Factory

4.3.1 Method of simulation

The method of simulation has been split into several steps, this has been done to ensure the procedure reflects the grid under evaluation as close to the actual grid as possible. The steps for setting up the simulations are as follows:

- Gathering information of real grid examples
- Establishing the grids in a proper simulation tool
- Generating load- and charging profiles
- Setting up harmonic data
- Placement of EVs
- 0-100% simulated penetration of EVs
- Choosing interesting grid examples from the grid pool

This report aims to investigate the impact of EVs on a wide variety of grids, and for that purpose it has been required to collect data from grids not likely to match each other. In order to accomplish this, this report contains grid data from the following countries; Denmark, Spain and Italy. The entire pool of grids, consist of 10 Danish, 9 Spanish and 2 Italian grids.

Establishing the grids in a proper simulation tool

The grids have been established in the DIgSILENT ® PowerFactory.

The calculation program PowerFactory, is a computer aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization.

Generating Load and Charging profiles

To be able to make a precise simulation of the chosen grids, different profiles of loads have to be taken into account. This covers load profiles for: Every household, EVs and additional network feeders connected to the same low-voltage transformer. In order to achieve a precise result of the simulations of the grids, a range of load profiles depending on the number of customers and a range of charging profiles depending on the number of EVs have been included in the simulation tool, PowerFactory.

- Consumer base load
- EV Charging profile
- Accumulated Consumer base loads for additional feeders

The consumer base load is representing the load already present in the grid, due to ordinary households. This base load is based upon averaged country specific measurements, i.e. to a Danish grid the consumer base load is based on an average Danish load profile. The consumer base load is furthermore influenced by a diversity factor, and will thereby appear diminishing relatively as the number of consumer grows.

For this analysis, three different charging profiles, User dependent, Timer Based and Load dependent have been included in this analysis, representing the load of EVs. The charging profiles are country specific as the traffic patterns differ slightly from country to country. Furthermore the load dependent charging profile must be adapted to the country specific load profile.

Details of the load profiles and charging profiles can be found in *D4.3 Parameters for Assessment of EVs impact on Low-voltage Grid*.

Setting up harmonic data
Two different harmonic sources have been added to the simulation tool, PowerFactory.

- Consumer base load background noise
- Harmonic source for EVs

<u>Consumer base load background noise</u>
The harmonic component of the households/base load is measured values from Christmas Eve in Denmark, and has been chosen to ensure a kind of worst case scenario. The base loads implemented in the grids are containing a harmonic source to illustrate the background noise already present in the grid, even before

any EVs are to be implemented. The background noise is not a symmetrical loading. The harmonic source of the base load is as shown in the table below:

Consumer BaseLoad Background Noise			
Harmonic	Phase 1	Phase 2	Phase 3
	I_h/I_n	I_h/I_n	I_h/I_n
Order	%	%	%
3	9,812012	10,55846	9,647828
5	6,107552	5,966593	7,035332
7	3,129378	2,680015	2,205014
9	2,519235	2,976302	2,242232
11	1,167895	1,396946	1,230607
13	0,5661846	0,574728	0,489181
15	0,715251	0,846662	0,480699
17	0,579144	0,741237	0,582098
19	0,2370915	0,347408	0,369355
21	0,2402822	0,190463	0,101607
23	0,1975107	0,148217	0,090387
25	0,1507719	0,084557	0,048903

Table 4.3.1 Emission values of base load (existing load)

Harmonic source for EVs

Two different harmonic sources for EVs are used in this analysis.

Each harmonic source illustrates the harmonic behavior of the EVs, when charging with the User dependent –and Timer based charging scenarios. This harmonic source is an average with respect to the maximum values of each individual EV included in the measurements in D4.2 Recommendation on grid-supporting opportunities of EVs”, when charging at maximum power.

The second harmonic source used in this report has been created to define the harmonic behavior of EVs when charging with less than maximum power. This is due to the fact that when charging with regards to the Load dependent charging scenario, an EV will not be charging at maximum power. This harmonic source is based on the measurement performed in “D4.2 Recommendation on grid-supporting opportunities of EVs”, and is an average with respect to the maximum values of each individual EV at any power range.

For User dependent/Timer based charging as for Load dependent charging, the average of the individual EV has been chosen due to the fact that different EVs have different harmonic spectrums. Thus EVs connected to the same grid probably do not have the same harmonic spectrum. More details on the harmonic sources can be found in the Appendix. The table below shows the harmonic emissions from the two sources used for this analysis. The IEC limits of the individual harmonic order for a 16A EV on board-charger are shown for information:

Harmonic sources							
Harmonic order	UD/TB	LD	IEC limits	Harmonic order	UD/TB	LD	IEC limits
	I_h/I_n %				I_h/I_n %		
2	0,49%	0,78%	6,75%	14	0,11%	0,17%	0,82%
3	7,48%	10,33%	14,38%	15	0,52%	0,93%	0,94%
4	0,19%	0,27%	2,69%	16	0,08%	0,12%	0,72%
5	2,31%	3,30%	7,13%	17	0,52%	0,86%	0,83%
6	0,16%	0,22%	1,88%	18	0,08%	0,12%	0,64%
7	1,88%	2,71%	4,81%	19	0,64%	0,91%	0,74%
8	0,14%	0,18%	1,44%	20	0,09%	0,11%	0,58%
9	1,37%	2,13%	2,50%	21	0,42%	0,58%	0,67%
10	0,12%	0,14%	1,15%	22	0,09%	0,12%	0,52%
11	1,08%	1,29%	2,06%	23	0,39%	0,55%	0,61%
12	0,11%	0,15%	0,96%	24	0,06%	0,13%	0,48%
13	0,82%	1,50%	1,31%	25	0,32%	0,48%	0,56%

Table 4.3.2 Emission levels of EVs and IEC limits for 16A apparatus

It should be noted that the relative emission levels for the 13^{th}, 17^{th} and the 19^{th} harmonic order in the load dependent (LD) scenario exceed the relative IEC limits for 16A apparatus.

Location of EVs

The EV placement strategy chosen is a strategy where the EVs are distributed along the feeder. The EVs are placed as single phase units switching between the three phases (a, b, c) for every EV, based on a voltage ranking. Thus, the EV location is neither overly pessimistic (worst case) nor optimistic (best case), but still errs on the side of caution (is closer to worst case than best case).

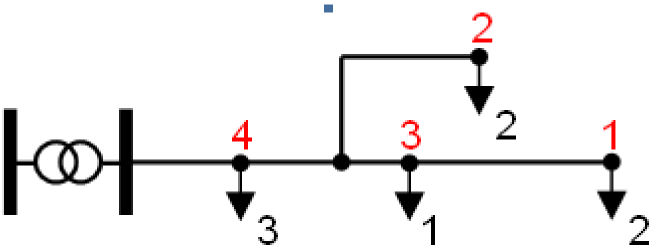
- Worst case
  The EVs are placed in the nodes with the lowest voltage. If a node has several customers connected to it, then each of these customers will get an EV, before EVs are placed in any of the other nodes.
- Distributed
  The EVs are placed in the nodes with the lowest voltage. If a node has

several customers connected to it, only one of them will get an EV, before moving on to the next node.

- Best case
  The EVs are placed in the nodes with the highest voltage. If a node has several customers connected to it, then each of these customers will get an EV, before EVs are placed in any of the other nodes.

The example below shows a feeder with voltage ranking of the nodes. Black numbers denote the number of customers. Red numbers are node names and denote the voltage ranking of nodes from worst/lowest voltage (1) to best/highest voltage (4). Applying the above EV placement strategies will place EVs in the nodes in the following order:

- Worst case: 1a,1b,2c,2a,3b,4c,4a,4b
- Distributed: 1a,2b,3c,4a,1b,2c,4a,4b
- Best case: 4a,4b,4c,3a,2b,2c,1a,1b



EV penetration

Every simulation will revolve around penetrating the grid with EVs. This is done by sequentially implementing from 0-100% EVs to the grid, by adding one EV at the time until 100% penetration is reached. By using this approach, the development can be followed as the penetration increases. The penetration can be described by following formula:

$$EV\ penetration = EVs\ per\ household = \frac{EVs}{households}$$

Choosing interesting grid examples from the grid pool

All grids have been subject to a base case simulation as described in section 4.3.3.1. For the final part of the simulation method, the entire grid pool will selectively be deducted to six grids, which contains PQ issues to be investigated further. The chosen grids will then be tested in regards to a variety of simulation scenarios to confirm the grids reaction on these scenarios.

4.3.2 Treatment of data.

When treating the output data from the simulations into usable and graphical representation in this report, the data has to be converted into a table form. The output of every simulation is a huge data mass, this is due to the way the outputs have been chosen to be extracted from PowerFactory. When simulating a grid, the output contains three different output categories, namely voltage, grid capacity and harmonic distortion.
Each of these categories again contains one data-file per implemented EV in the grid, plus a base scenario of 0% EV penetration. In order to handle such a huge amount of data visually, every output data file from 0-100% EV penetration has been converted into a duration-curve for every increment in EVs for all of the three categories.

The duration curve is containing every result from every node in the grid.

In the duration curve where the harmonics are depicted, the limit in the curve of the harmonics has been normalized for every harmonic order, and thereby making it easier for the reader.

The above clarification of the data handling is underlined as an example of data from Grid 1, in the analysis below:

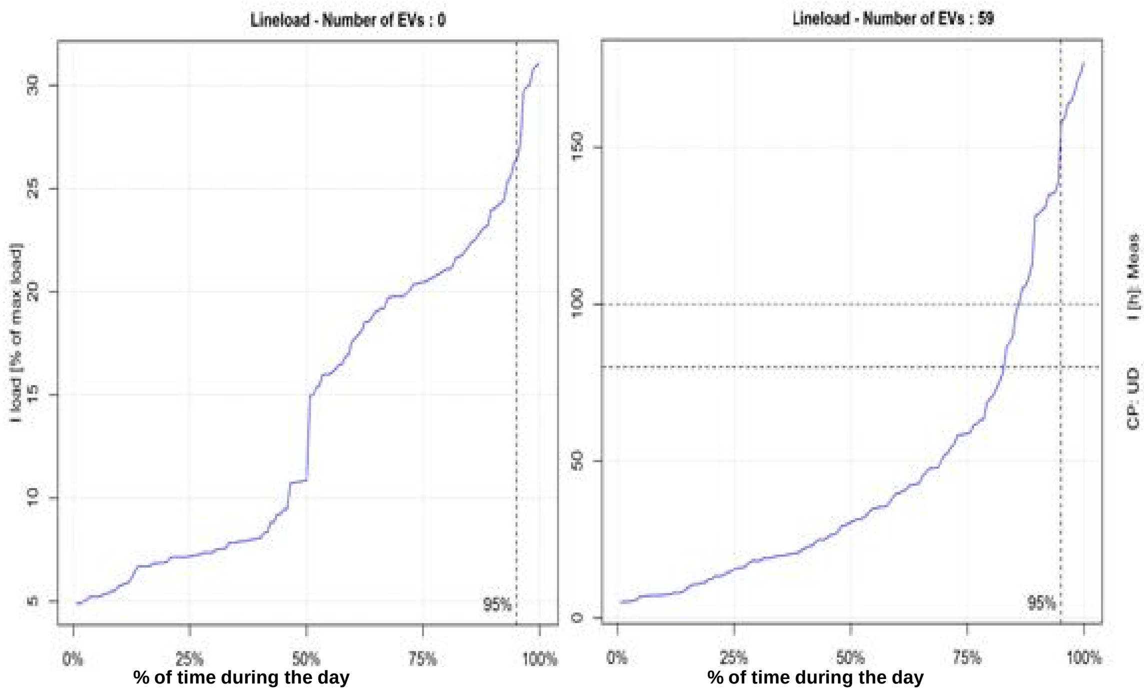


Figure 4.3.1 Duration curves for Line loads.

Figure 4.3.1 shows two line load scenarios, the base scenario (to the left) and the final scenario (100 % EV penetration, to the right). The figure shows two different pictures of the line load, the base scenario and the scenario with a 100 % EV penetration. To determine whether an asset is overloaded or not, a limit of 100% of the capability of the asset is selected. It is clear at the base scenario that the line load of the grid is nowhere near getting overloaded, since the peak load is 30%. The scenario with 100 % EV penetration shows a peak load close to 200 % of the line load the grid is actually capable of, and that the line is overloaded 10 % of the time. Therefore the limit of EVs able to be connected to this grid with respect to the line load is less than 100% EV penetration. The exact limit can be found by analyzing the other penetration rates.

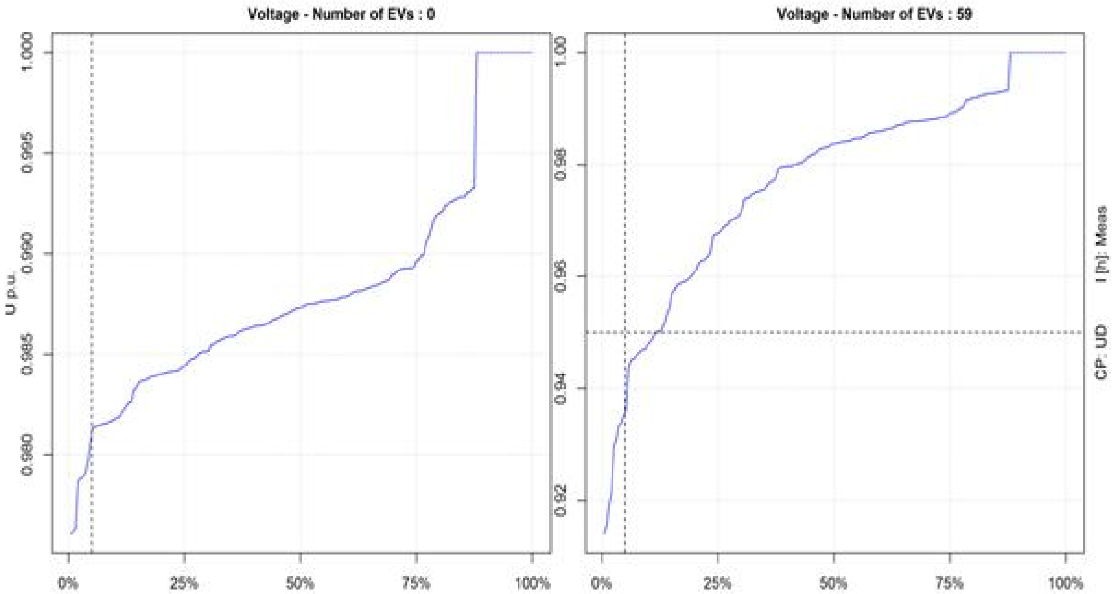


Figure 4.3.2 shows two voltage scenarios, the base scenario (to the left) and the final scenario (100 % EV penetration, to the right).

Figure 4.3.2 shows two different pictures of the voltage, the base scenario and the scenario with a 100 % EV penetration. Due to technical reasons the scaling of the y-axis is different in the two pictures. To determine whether the voltage limit is violated or not, a voltage drop of 5% is selected, as this is a commonly used design criteria. The maximum allowed duration of voltage violation is 5% in accordance with *EN 50160 Voltage characteristics of electricity supplied by public electricity networks*. It is clear at the base scenario that the voltage of the grid is nowhere near getting below the required 95% (0.95 p.u.) of the nominal voltage level, more than 5% of the time. Whereas the scenario with 100 % EV penetration, shows a voltage dive to 95% of the nominal current 5% of the time, which is not acceptable. Therefore the limit of EVs able to be implemented in this grid with respect to the voltage is found in between 0- 100% EV penetration.

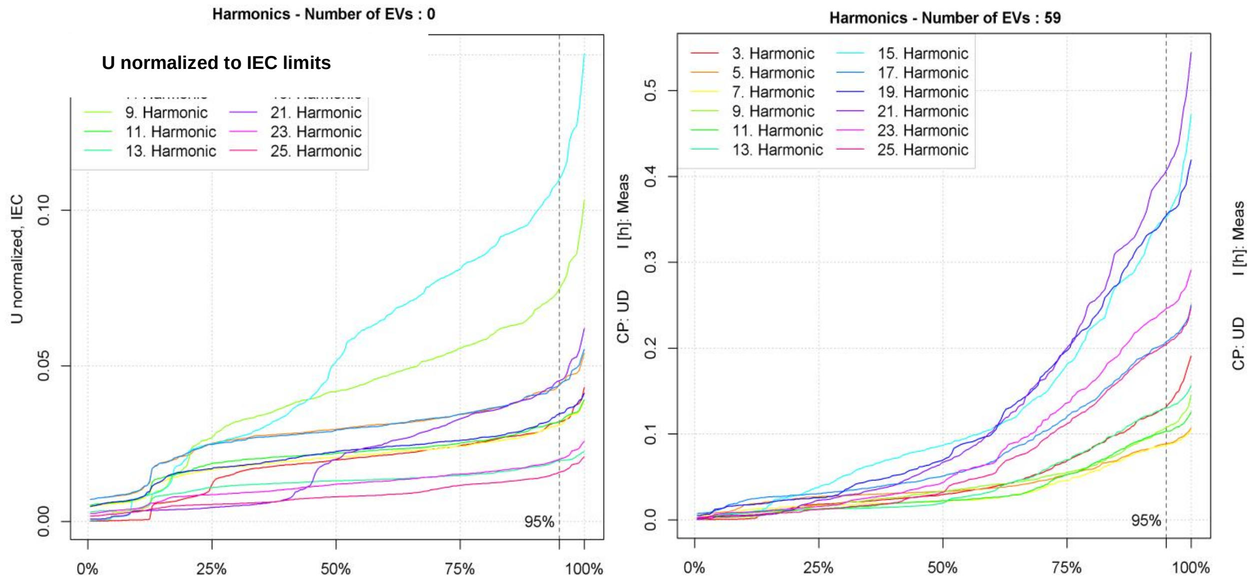


Figure 4.3.3 shows two harmonic scenarios, the base scenario (to the left) and the final scenario (100 % EV penetration, to the right).

The Figure 4.3.3 shows two different pictures of the harmonics, the base scenario and the scenario with a 100 % EV penetration. To determine whether the harmonic limits are violated or not, limits have be chosen in accordance with *EN 50160 Voltage characteristics of electricity supplied by public electricity networks*. The maximum allowed duration of harmonic violation is 5% in accordance with *EN 50160.* The base scenario shows the level of harmonics in the grid is less than 11% of the low-voltage emission limits, 95 % of the time. The scenario with 100% EV penetration has a change in the level of harmonics less than 40% of the low-voltage emission limits, 95% of the time. It can be concluded, that in this scenario the grid is capable of handling the harmonics from EVs.

4.3.3 Simulations with User Dependent Charging

4.3.3.1 With background noise

The entire pool of grids has been simulated with a user dependent charging strategy. This has been done in order to be able to analyse which one of the grids is showing signs of a weakness when looking at power quality under the loop.

This simulation is the "base-case", and therefore, this scenario has been used to sort the entire grid pool down to the six chosen grids to be further investigated.

The composition of this charging strategy is as follows:

- Every household is simulated with a base load
- EVs are simulated from 0-100 % penetration
- EVs are sequentially implemented as single phase loads on the three phases by turn
- User dependent charging profile
- UD/TB harmonic source

4.3.3.2 Without background noise, with IEC limits and measured noise

The six chosen grids have been simulated, only with respect to calculating voltage distortion derived from the EVs. This procedure has been done as a double scenario by changing the harmonic EV source between the UD/TB harmonic source and the LD harmonic source according to Table 4.3.2. This has been done to determine the differences between real measurements and the IEC limits for distortion, and in addition to determine whether or not the calculation method performed by PowerFactory and the IEC calculations is in compliance.

The composition of this simulation is as follows:

- Every household is removed from the simulation
- EVs are simulated from 0-100% penetration
- EVs are sequentially implemented as single phase loads on the three phases by turn
- User dependent charging profile
- UD/TB harmonic source according to Table 4.3.2

4.3.4 Simulations with Timer Based Charging

4.3.4.1 With background noise

In this simulation scenario the chosen grids, Grid 1-6, are simulated with regards to assess whether a Timer Based charging profile is improving the grids' capability to handle a great penetration of EVs, compared to both User defined and load dependent charging strategies.

The composition of this charging strategy is as follows:

- Every household is simulated with a base load
- EVs are simulated from 0-100% penetration
- EVs are sequentially implemented as single phase loads on the three phases by turn
- Timer Based charging profile
- UD/TB harmonic source

4.3.5 Simulations with Load Dependent Charging

4.3.5.1 With background noise

In this simulation scenario the chosen grids, Grid 1-6, are simulated with regards to assess whether a Load dependent charging profile is improving the grids' capability to handle a great penetration of EVs, compared to both User defined and Timer Based charging strategies.

The composition of this charging strategy is as follows:

- Every household is simulated with a base load
- EVs are simulated from 0-100% penetration
- EVs are sequentially implemented as single phase loads on the three phases by turn
- Load dependent charging profile
- Load dependent harmonic source (OPT)

Information of grid selection

This report aims to investigate the impact of EVs on a wide variety of grids, and to do that, it is needed to collect data for grids not likely to match each other. In order to accomplish this, this report contains grid data from the following countries; Denmark, Spain and Italy. The entire pool of grids, consists of 10 Danish, 9 Spanish and 2 Italian grids.
An investigation on the entire grid pool has been performed, and out of this investigation 6 grids, which are of special interest when looking at the three power quality parameters have been chosen.

Data for the chosen grids can be seen in the following table:

Grid information					
Grids	Length	Transformer size	Short-ciruit Current	Avg. impedans	Comments
.	102m	400	5.77KA	0,079 Ω	Surburban grid
2	109m	400	5.77KA	0.101 Ω	Surburban grid
3	60m	200	5.77KA	0.166 Ω	Surburban grid
4	101m	400	11.5KA	0.219 Ω	Surburban/city grid
5	109m	630	7.2KA	0.063 Ω	City grid
6	74m	630	7.2KA	0.087 Ω	City grid

Table 4.3.3 Grid data

The chosen grids do all have that in common that they are only supplying households, and are not polluted by industry or bigger production facilities. The things which differ from grid to grid, is the grid topology e.g. type of cables, length of cables, size of transformer together with the number of consumers and the density of the consumers in the grid. The diversity of the grids gives different characteristics of the different grids related to harmonics, but also related to capacity and voltage drop.

5 Analysis of results

Comparison of IEC calculations and simulations

This section will make a comparison of IEC calculations and the PowerFactory simulations. This is done to investigate how the calculations and simulations differ, including which parameters are influencing the results.

These calculations have been made without any background noise, and are only taking the harmonic distortion caused by the EVs into consideration. This is done by looking at whether the distortion of the EVs is surpassing the LV voltage distortion limits. The table will only show the state of grids with 100% EV penetration in order to show a direct comparison between the two calculation methods.

The results from the IEC and PowerFactory calculations are as follows:

IEC CALCULATIONS				
Grid Info			3. Harmonic	15. Harmonic
Grid	N EVs	n EVs (IEC)	Harmonics % / LV limit	Harmonics % / LV limit
1	184	184	94%	27%
2	167	167	86%	33%
3	53	53	77%	28%
4	339	339	166%	33%
5	59	59	133%	33%
6	80	80	277%	80%

POWERFACTORY SIMULATIONS				
Grid Info			3. Harmonic	15. Harmonic
Grid	N EVs	n EVs (PF)	Harmonics % / LV limit	Harmonics % / LV limit
1	184	184	45%	95%
2	167	167	77%	220%
3	53	53	39%	99%
4	339	339	110%	250%
5	59	59	12%	32%
6	80	80	119%	155%

- N EVs is the number of consumers in the grid, and will be equal to the number of EVs in the grid when looking at 100 % penetration
- n EVs is the number of EVs the grid can absorb before hitting the harmonic distortion limit
- Harmonic % / LV limit is the percentage of how much of the LV limit is occupied at 100 % EV penetration in the specific grid, at the respective calculation method.

Table 4.3.1 IEC calculations and PowerFactory simulations

Sub conclusion:
When examining the results from the comparison between IEC and PowerFactory simulations, the IEC calculations are generally obtaining significantly higher harmonic distortion at the 3rd harmonic order. When looking at the 15th harmonic order, the PowerFactory simulations are widespread and give significantly higher values for the harmonic distortion.

The IEC calculation method is very simplified and strongly dependent on the transformer capacity and the short-ciruit level. In the IEC calculations the emission limits for each EV are proportional to the share of the transformer capacity. The Power Factory simulations are strongly dependent on the location of each EV and the short-ciruit level. In the PowerFactory simulations the distortion is calculated for each individual node in the grid. Situations where EVs are located relatively close to the transformer give better results than situations where EVs are located relatively far from the transformer. Thus the location of the EVs is of great importance. In both methods the short-ciruit level has an influence on current emissions impact on the voltage.

Influence of Charging Strategy

This section contains data on how a change in charging strategy influences the PQ and limitations of the grids. The simulation contains the three charging scenarios: User dependent charging, Timer Based charging and Load dependent charging.

A clarification of the tables and the results of the charging strategies can be seen in the tables below.

Terms used in the charging strategy tables	Clarification of the terms used
Country	The country in which the grid is located
Grid	The particular grid name under examination
N EV's	The maximum number of EVs/Consumers in the grid
Line load	The number of EVs the grid can contain before a violation of the line load
Voltage	The number of EVs the grid can contain before a violation of the voltage
Harmonics	The number of EVs the grid can contain before a violation of the harmonic emission
n EV's	The maximum number of EVs the grid can contain without violating any of the three parameters above
Abb.	An abbreviation of which of the three parameters is the most critical, VHL mean Voltage is the most limiting parameter, then harmonic and last Line load.
Comments	The comment section contains information on the state of the grid with a EV penetration of 100 %

Table 4.3.2 Clarification of columns in Table 4.3.3, Table 4.3.4 and Table 4.3.5

User dependent charging profile							
PowerQuality							
Grid	N EV's	Line load	Voltage	Harmonics	n EV's	Abb.	Comments
		100/100%	0,95p.u. / 95%	1 /95%			
1	184	125	119	184	119	VL(H)	L: 132%/100 % V: 0.935/95 % H15: 0.37/95 %
2	167	94	21	0*	21	VL(H)	L: 160%/100 % V: 0.90/95 % H15: 0.6/95 %
3	53	27	5	0*	5	VL(H)	L: 130%/100 % V: 0.925/95 % H15: 0.6/95 %
4	339	120	48	0	0	HVL	L: 240%/100 % V: 0.82/95 % H15: 5.2/95 %
5	59	26	28	59	26	LV(H)	L: 210%/100 % V: 0.938/95 % H19: 0.72/95 %
6	80	37	69	37	37	LHV	L: 275%/100 % V: 0.94/95 % H21: 2.0/95 %

*) With no EVs the limit is exceeded. With a few EVs connected, the harmonic level decreases below limit.

Table 4.3.3 Results of User dependent charging

User dependent charging summary:
The results of using a charging strategy which allows the consumer to charge the EV whenever it is suitable, clearly states problems at almost every parameter under consideration. The results from the 6 grids under evaluation are not consistent, as depicted in the table the limiting factor for the grids is interchanging between all of the three parameters. An important thing to notice is the fact that every grid has its limitations, meaning that none of the 6 grids are able to absorb a 100 % penetration of EVs. The range is from approx. 10% to 70% penetration of EVs.

Timer Based charging profile							
PowerQuality							
Grid	N EV's	Line load	Voltage	Harmonics	n EV's	Abb.	Comments
		100/100%	0,95 pu /95%	1 /95%			
1	184	132	132	184	132	LV(H)	L: 135%/100 % V: 0.94/95 % H15: 0.45/95 %
2	167	107	52	0*	167	VL(H)	L: 150%/100 % V: 0.91/95 % H15: 0.67/95 %
3	53	29	9	0*	9	VL(H)	L: 120%/100 % V: 0.93/95 % H15: 0.65/95 %
4	339	31	25	0	0	HVL	L: 240%/100 % V: 0.82/95 % H21: 4.9/95 %
5	59	32	36	59	32	LV(H)	L: 210%/100 % V: 0.938/95 % H21: 0.45/95 %
6	80	30	66	33	30	LHV	L: 275%/100 % V: 0.94/95 % H21: 2.2/95 %

*) With no EVs the limit is exceeded. With a few EVs connected, the harmonic level decreases below limit.

Table 4.3.4 Results of Timer based charging

Timer Based charging summary:

The results of using a charging strategy which allows the consumer to charge the EV, outside of grid load peaks, clearly states problems at every parameter under consideration.

When looking at Timer Based charging compared to User dependent charging, it is noticeable that the number of EVs that the grids can absorb does not change significantly. This is due to the fact that all EVs start charging at the same time after the prohibited period is over. Common to Timer Based and User dependent charging is that neither of the grids can absorb a 100 % penetration of EVs. The range is from approx. 20 % to 75 % penetration of EVs. With respect to User Dependent charging, it can be concluded that using a Timer Based charging profile, in all situations, will be able to postpone grid reinforcement till a later stage in all situations.

Load dependent charging profile							
PowerQuality							
Grid	N EV's	Line load	Voltage	Harmonics	n EV's	Abb.	Comments
		100/100%	0,95 pu /95%	1 /95%			
1	184	184	184	184	184	N/A	L: 37%/100 % V: 0.97/95 % H15: 0.7/95 %
2	167	167	167	0*	167	N/A	L: 25%/100 % V: 0.97/95 % H15: 1.15/95 %
3	53	53	53	0*	53	N/A	L: 17%/100 % V: 0.99/95 % H15: 1.2/95 %
4	339	339	339	0*	339	N/A	L: 33%/100 % V: 0.97/95 % H15: 1.3/95 %
5	59	59	59	59	59	N/A	L: 45%/100 % V: 0.975/95 % H15: 0.15/95 %
6	80	80	80	80	80	N/A	L: 47%/100 % V: 0.98/95 % H15: 0.68/95 %

Table 4.3.5 Results of Load dependent charging

*) EVs are not charged during the peak hour, thus harmonics introduced by base-load is not influenced

Load dependent charging summary:

When looking at a load dependent charging profile with respect to the previous charging scenarios, there is a distinct difference between them. The load dependency in a charging profile ensures that the load coming from charging an EV at a given time is spread widely over the 24 hours of the day.

None of the grids in this scenario are experiencing any problems concerning the voltages or the line loads in the grid.

Sub conclusion:

The most important conclusion is the fact that overload and voltage violations can be avoided by introducing Load dependent charging without EVs having a significant impact on the harmonics.

The common picture is that thermal or voltage limits are exceeded before the harmonic limits are exceeded. Only for one single grid (grid 6) in the user dependent scenario, the harmonic limits are exceeded with the same number of EVs at approx. 45 % penetration of EVs. In the load dependent scenario 100 % penetration of EVs can be absorbed by the same grid.

It is worth noticing that all scenarios in three grids exceed the harmonic limit with 0 EVs connected to the grid, which means that the exceeding of the limit is caused by the existing load and not the EVs. For two of those grids in the User dependent and Timer based scenarios, the harmonics are actually damped by introducing EVs into the grids. In the Load dependent scenario this is not the case, as EVs are not charging at peak hours.

6 Analysis of influence of charging strategy and grid topology

This section will contain an analysis of the influence of charging strategies in the different grids, with concerns to the harmonics. It will be represented by showing the duration curves of the grids at 0 EVs and a random number of EV penetration of interest.

In both of the aforementioned duration curves, at picture of each scenario will appear, User dependent, Timer Based, Load dependent and the only EV scenario.

Grid 4

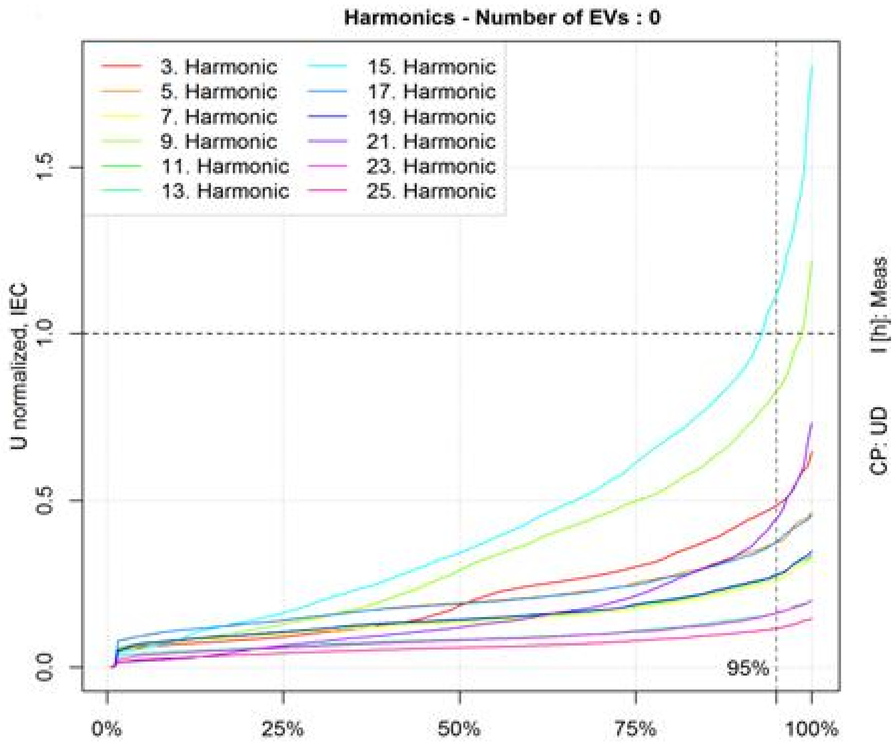


Figure 4.3.1 The current state of the grid, assuming zero EVs is implemented in the grid. As seen in the figure, it is already surpassing the Low-voltage limits of the grid.

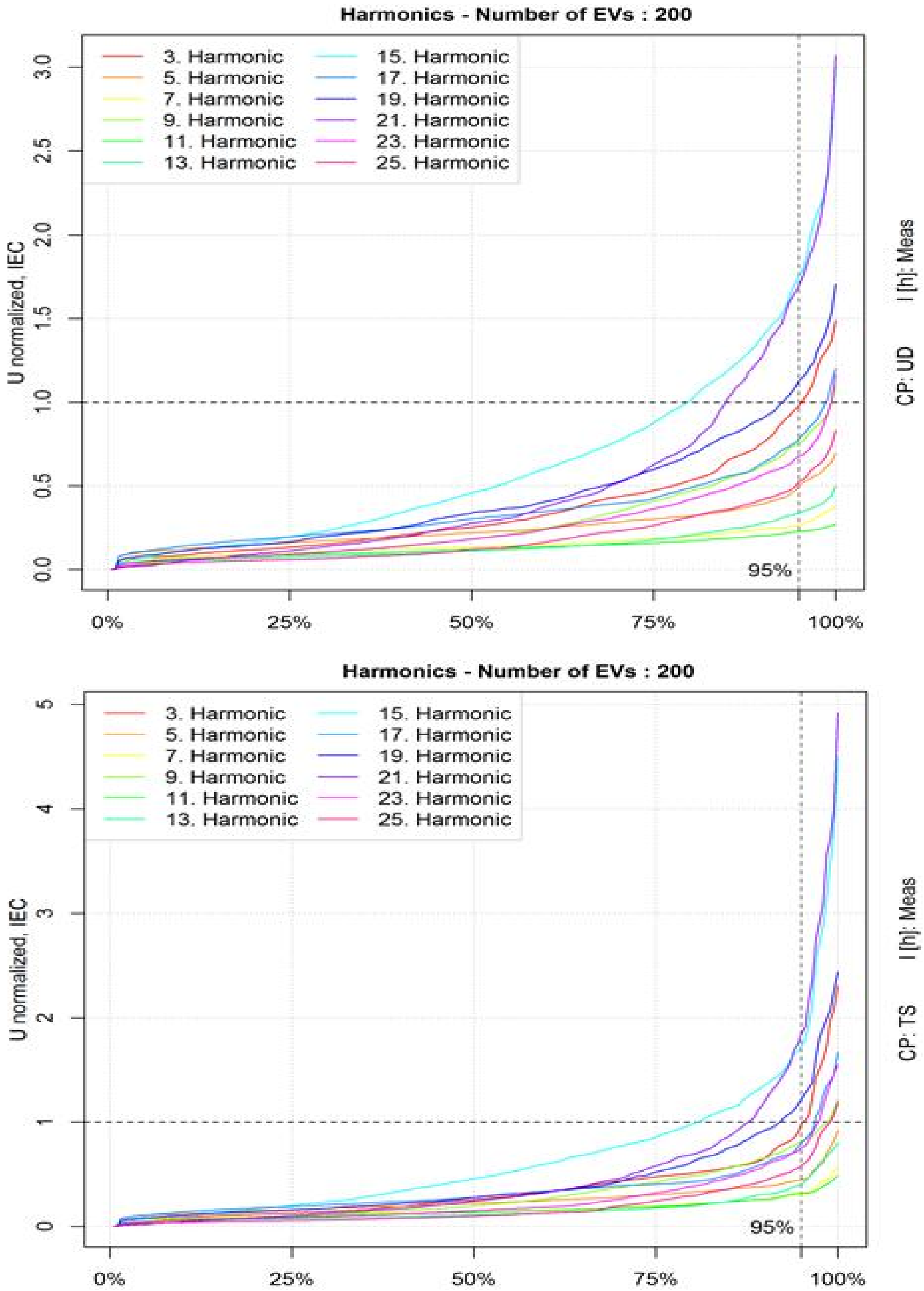


Figure 4.3.2 This picture contains two scenarios, at the top User dependent charging. The bottom picture is illustrating a Timer based charging strategy, both at 200 EVs.

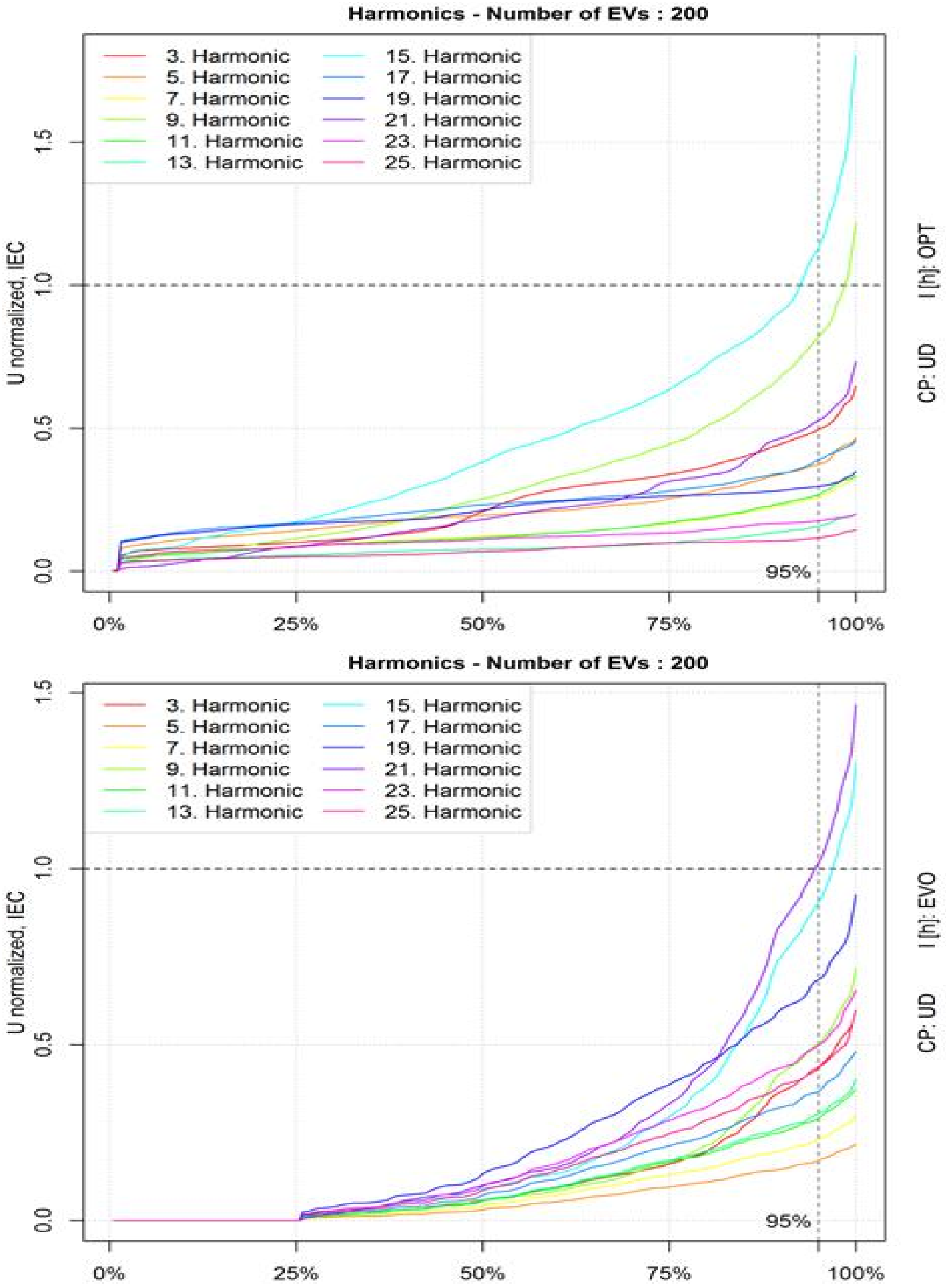


Figure 4.3.3 This picture contains two scenarios, at the top Load dependent charging. The bottom picture is illustrating a zero background noise scenario, both at 200 EVs.

When looking at the two scenarios from the Grid 4, it shows that by changing the charging strategy from User dependent→Timer Based→Load dependent there is a decrease in the multitude and number of harmonics which violate the limitations of the LV-grid. Furthermore, can it be concluded that it is the harmonic orders of a multiple of three which invokes the biggest violations of the grid limitations.

When looking at the zero background noise scenario, it shows that by only implementing EVs to the grid, it will still violate the limitations. Again it is the multiple of three harmonics which violate the limits, whereas the other harmonics is not surpassing the limit.

GRID 2

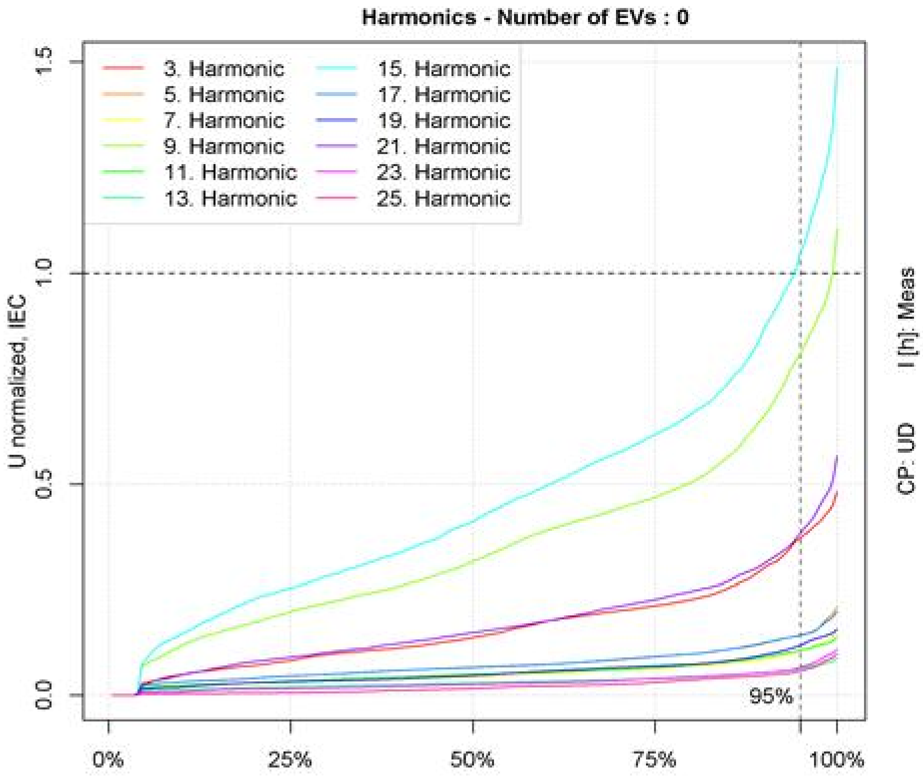


Figure 4.3.4 The current state of the grid, assuming zero EVs is implemented in the grid. As seen in the figure, it is already surpassing the Low-voltage limits of the grid.

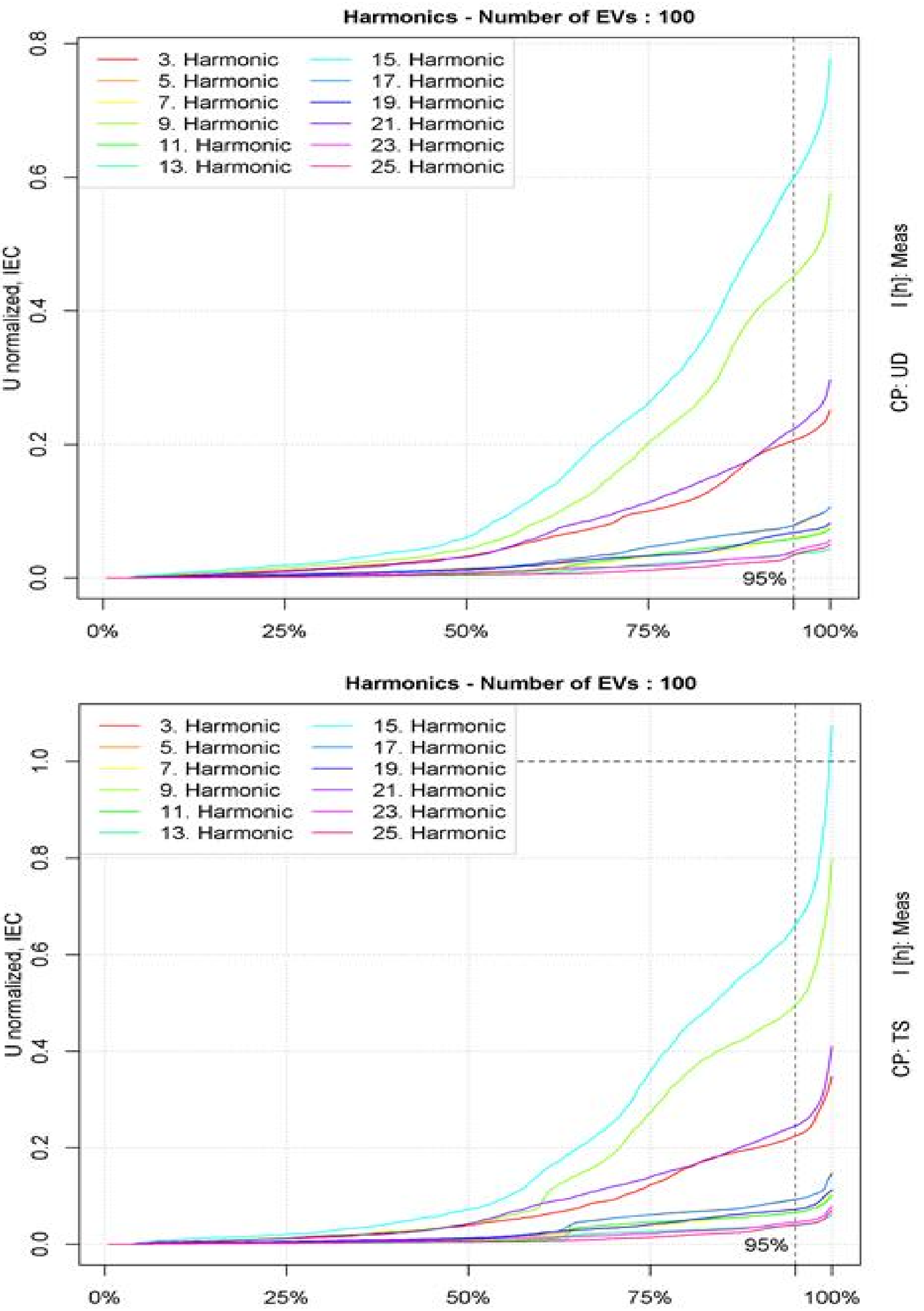


Figure 4.3.5 This picture contains two scenarios, at the top User x<dependent charging. The bottom picture is illustrating a Timer based charging strategy, both at 100 EVs.

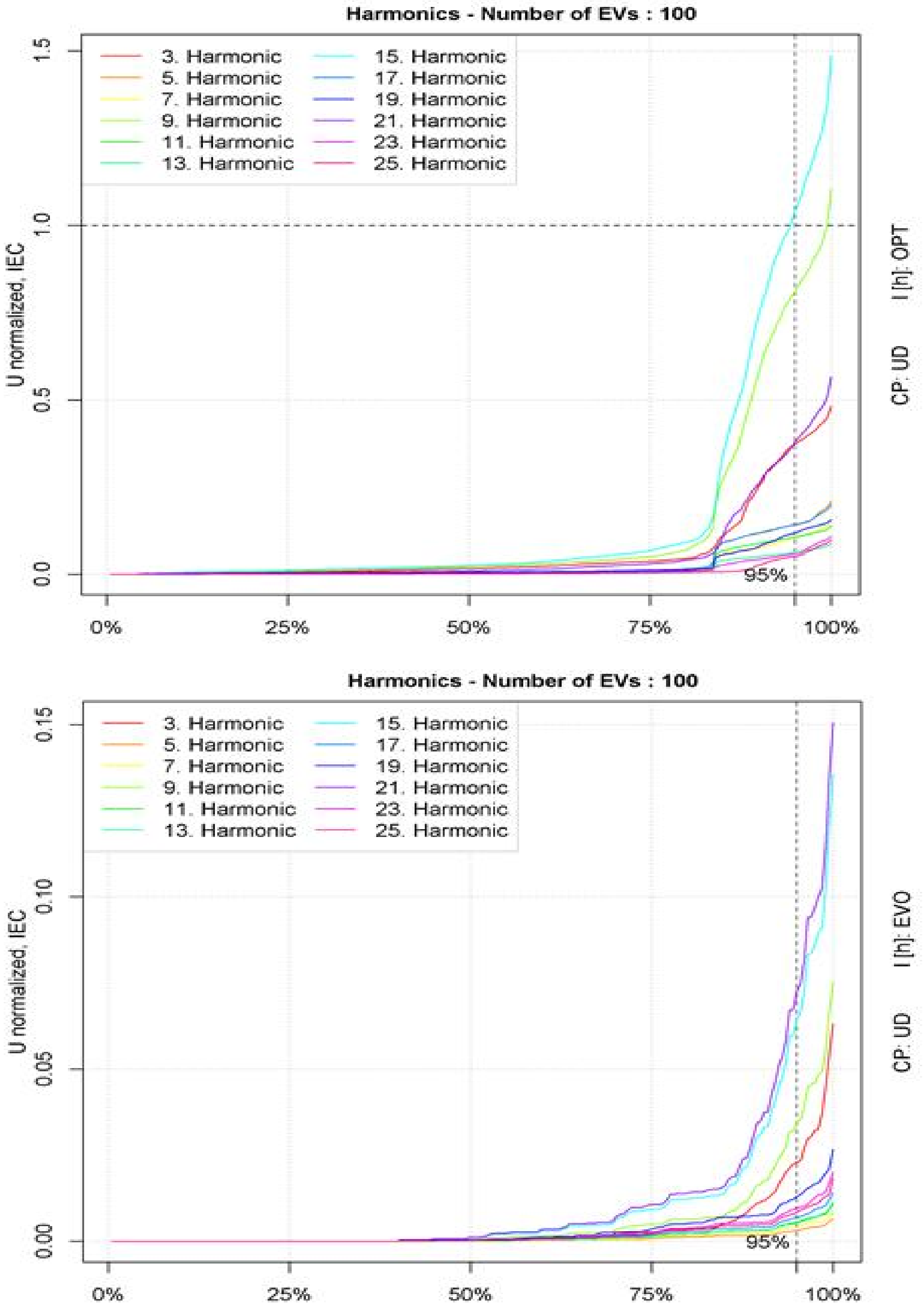


Figure 4.3.6 This picture contains two scenarios, at the top Load dependent charging. The bottom picture is illustrating a zero background noise scenario, both at 100 EVs.

When looking at the two scenarios from the Grid 2, it shows that by changing the charging strategy from User dependent→Timer based→Load dependent there is an increase in the amplitude of the harmonics, but opposite Grid 4, there is never a violation of the harmonic distortion boundaries (except when using a load dependent user profile). Furthermore, can it be concluded that it is the harmonic orders of a multiple of three which invokes the biggest concerns in regards to the distortion.

When looking at the zero background noise scenario, it shows that by only implementing EVs to the grid, you will not encounter problems with concerns to violating the limits of harmonic distortion. From the above observation, there is reason to believe that the already existing background noise present in the grid, is dominating compared to the added noise from the EVs.

Grid 5

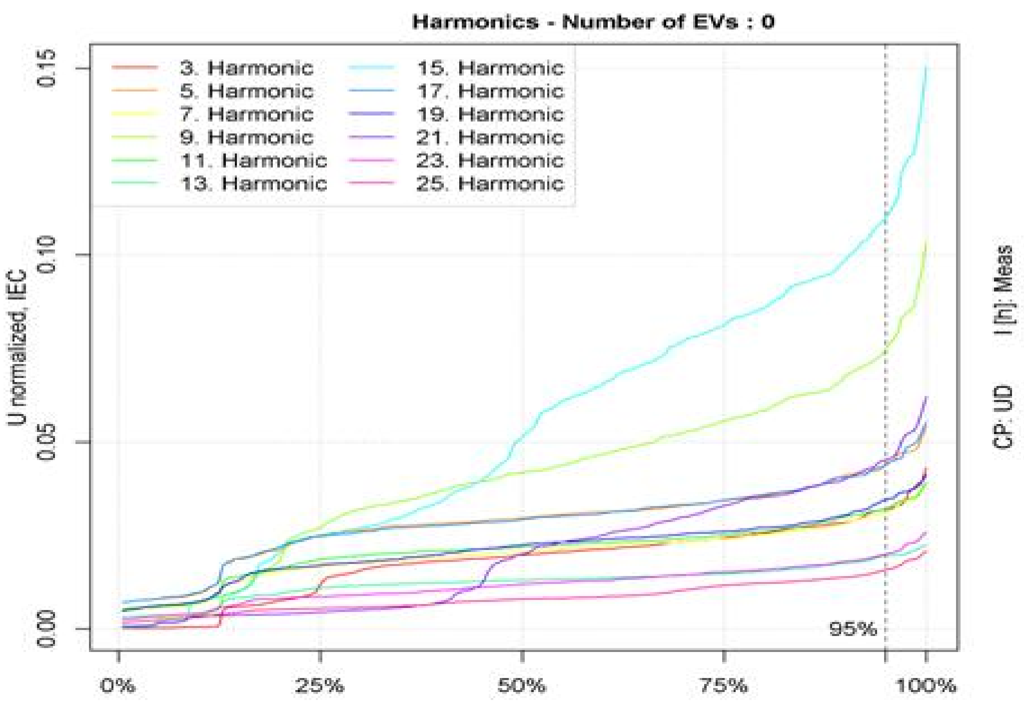
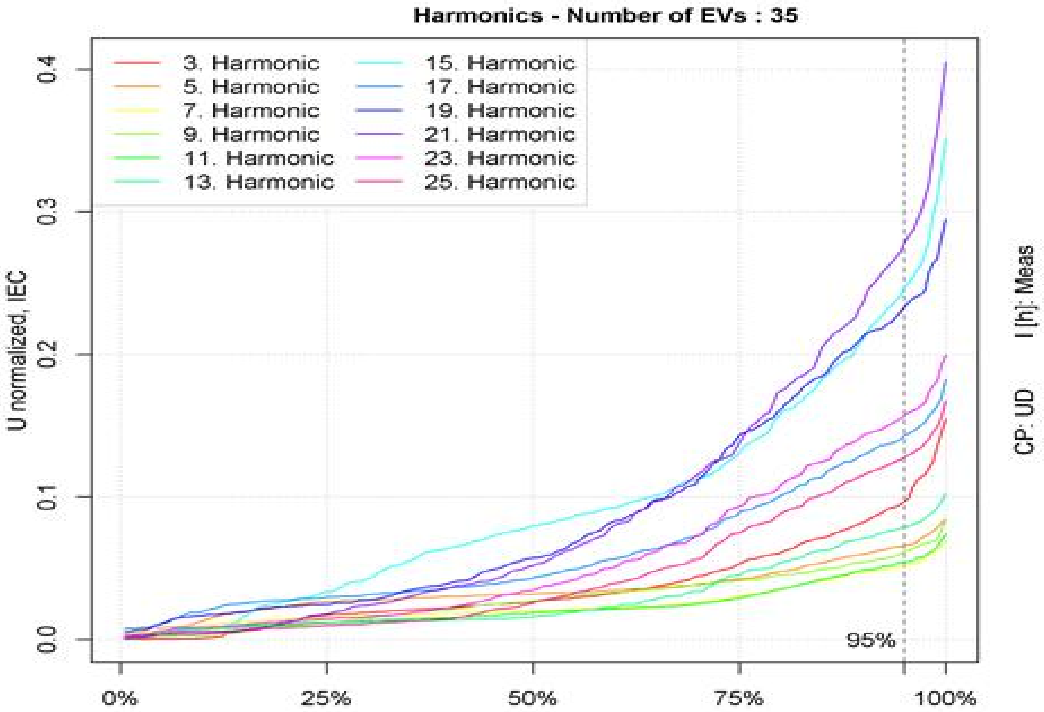


Figure 4.3.7 The current state of the grid, assuming zero EVs is implemented in the grid. As seen in the figure, it is already surpassing the Low-voltage limits of the grid.



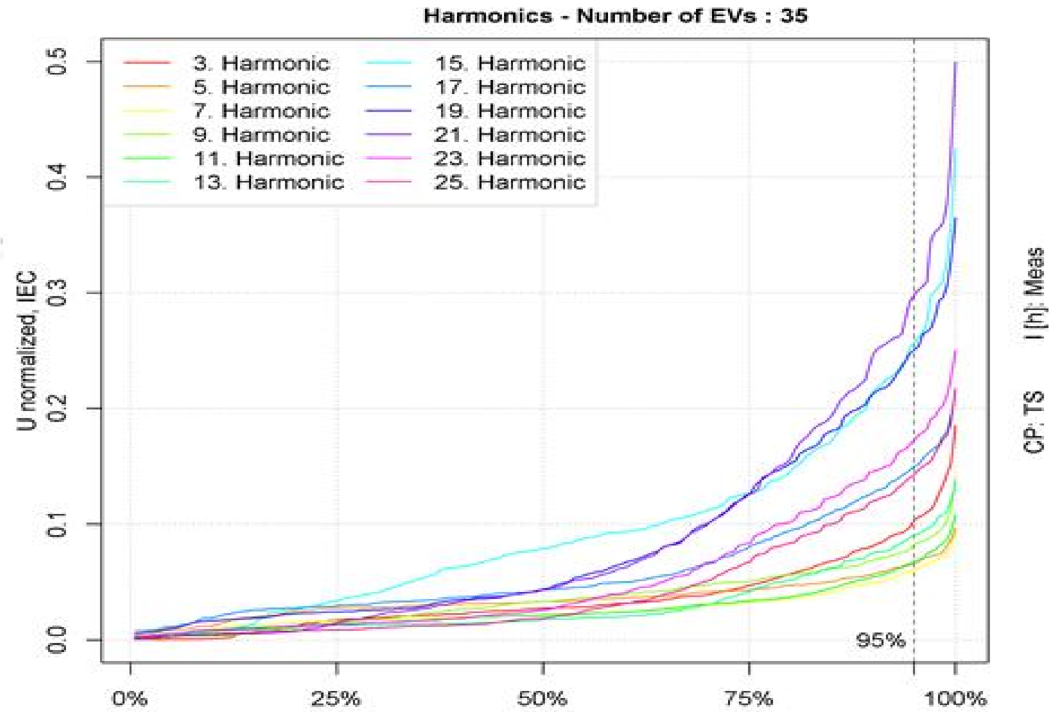
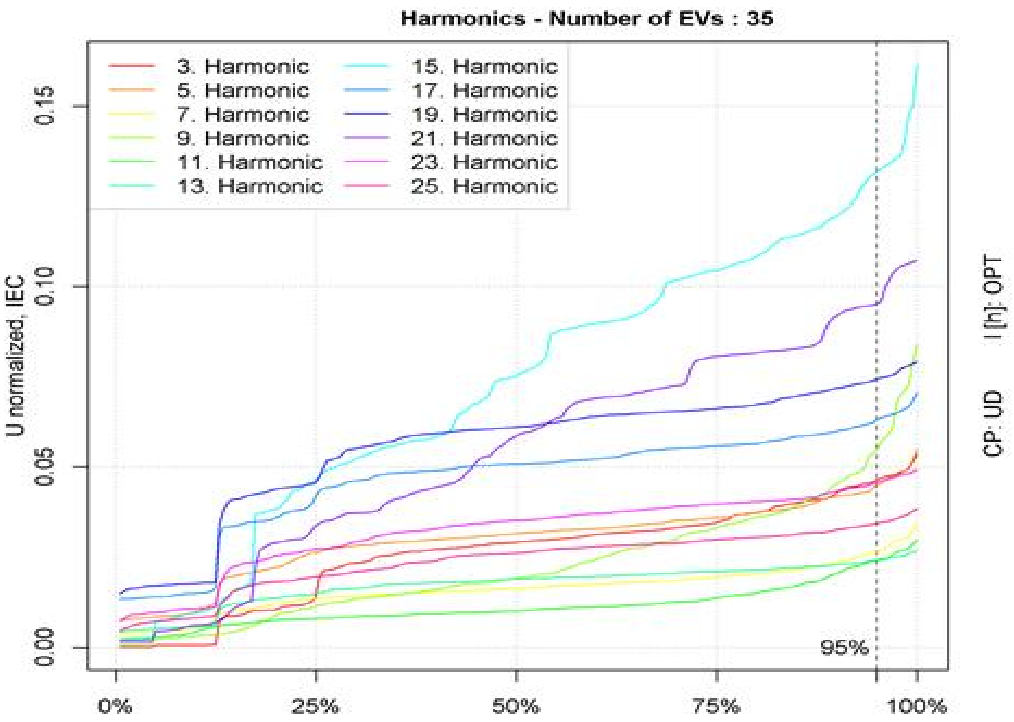


Figure 4.3.8 This picture contains two scenarios, at the top User dependent charging. The bottom picture is illustrating a Timer based charging, both at 100 EVs.



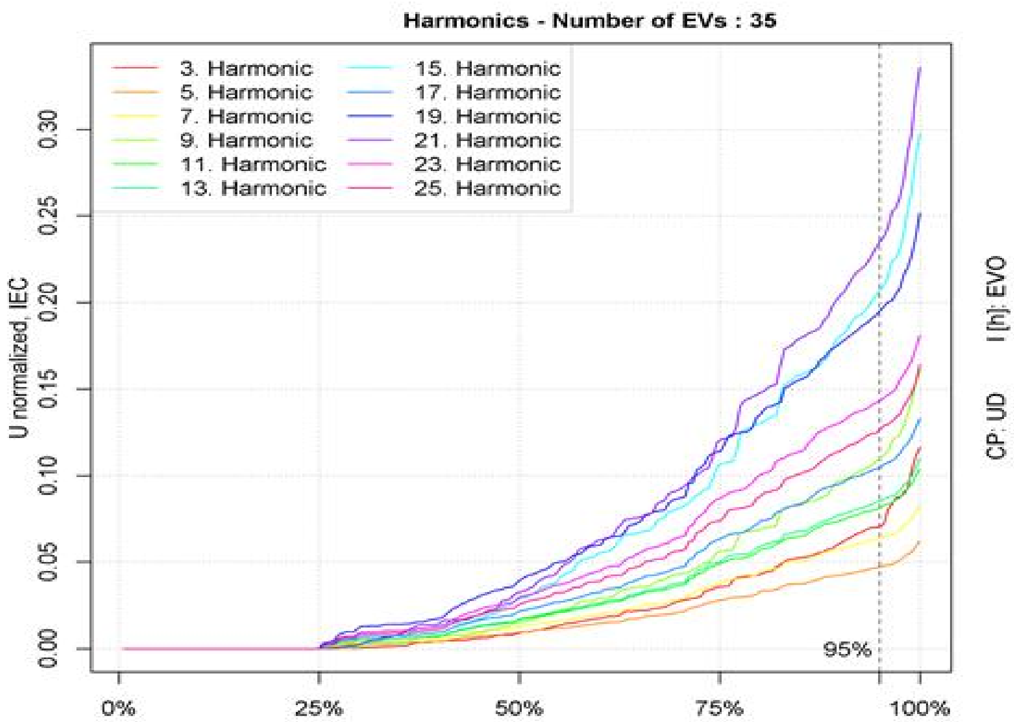


Figure 4.3.9 This picture contains two scenarios, at the top Load dependent charging. The bottom picture is illustrating a zero background noise scenario, both at 35 EVs.

When looking at the two scenarios from Grid 5, it shows that by changing the charging strategy from User dependent→Timer based it states a minor increase in the amplitude of the harmonics. It has to be noted that none of the charging

scenarios is violating the grid limits. As a side note, it can be concluded that it is the harmonic orders of a multiple of three which invokes the biggest harmonic voltage distortion.
When looking at Load dependent charging compared to the two previous charging strategies, it is noticeable that the grid is encountering less harmonic distortion.

When looking at the zero background noise scenario with user dependent charging, it shows a minor decrease when compared to the User dependent scenario incl. background noise. By that it can furthermore be concluded that it is the EVs which are the distorting part of this grid.

Sub Conclusion:
Despite higher emissions from each individual EV in the load dependent scenario, the general trend is a decrease in the total level of harmonics when applying this charging strategy. The decrease in the total level of harmonics is achieved as the maximum load is reduced in the load dependent scenario. I.e. that in relative numbers the harmonic emissions are increased by load dependent charging (due to charge power modulation), but in absolute numbers they are decreasing due to the reduced overall load.

In general harmonic orders of a multiple of three are the most significant harmonics. Typical the 15th and the 9th order compose the highest values relative to the limits followed by the 21th and the 3rd.

As shown in Table 4.3.3 Grid 4 has significantly higher average impedance compared to the other grids. All simulations and calculations show a greater impact on Grid 4 compared to the other grids. Thus a high short-ciruit level is of importance.

Furthermore, the analysis show where a large number of customers or EVs are connected to the same node in the grid results in a higher level of harmonics, especially harmonic orders of multiple of three. In real grids, cancelation to some extend of those harmonics would occur due to diversity of different EV chargers. A closer look at Grid 6 shows that the customers are located in relatively big groups far from the transformer which leads to higher levels of harmonics.

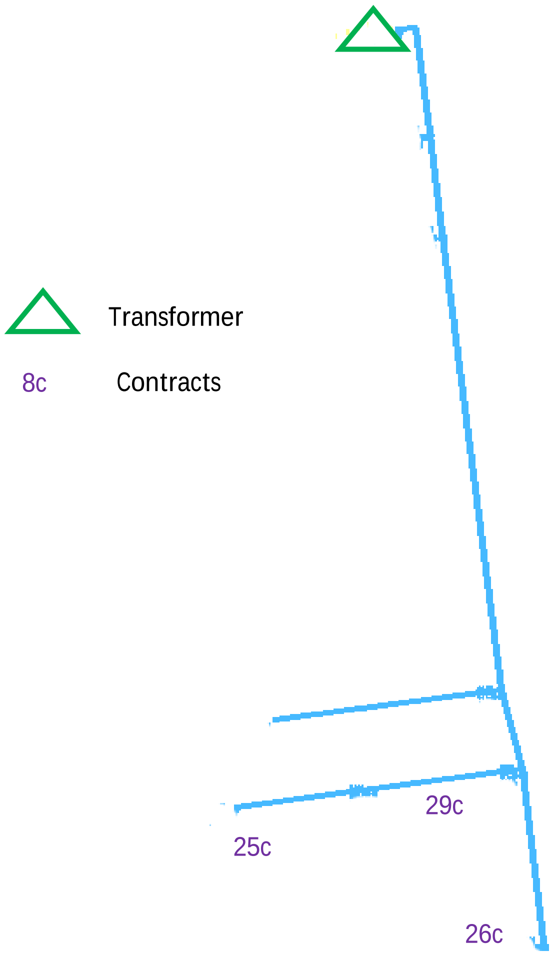


Figure 4.3.10 Topology of Grid 6

7 Perspectives

7.1 Improvement of knowledge

The studies carried out within the scope of this report are based on a number prerequisites and simplifications, for instance the chosen charging profile for load dependent charging, where the charging power in the peak hours is very limited. Additionally all EVs and loads were set to have the same level of harmonics respectively. In real life this is not the case, why the results should be treated with care.

As the results show in the previous chapter, it is very difficult to assess the impact on the grid as different methods give different results, why knowledge in this field should be improved, explicit taking the evolution of the use of the electricity grid into account. It is of importance also to include the evolution of the electricity grid up to today, as the local level of harmonics varies.

Measurements of power quality, including harmonics, are the key to gain knowledge in this field as local conditions must be considered in assessing power quality. Standardization related to EVs is covered by the emission standard EN 61000-3-2 *Electromagnetic compatibility (EMC) -- Part 3-2: Limits - Limits for harmonic current emissions (equipment input current <= 16 A per phase.)* The emission limits, which cover EVs, are set as absolute values. This has the disadvantage that the relative emission limits increase when charging power is reduced. Thus it is recommended to develop limits, taking into account reduction of charging power.

Even though, it is out of the scope of this report, it is worth mentioning that there is a need to develop emission limits between 2 and 150 kHz, so that disturbances emitted by EVs in this frequency range, do not disturb PLC communications used for smart metering and intended to be used in the Smart Grid.

In addition it is recommended to consider future interactions between EVs and DSOs when developing communication standards for EVs as this is a prerequisite to avoid violations of voltage and capacity limits in the low-voltage grid.

7.2 Distributed generation and new technologies

The scope of this assessment is to evaluate EVs impact on the existing grid with existing traditional loads. It must be noticed that this framework will change in the future. Distributing generation is emerging and results in more distorting units connected to the grid. Furthermore, new technologies is emerging as well, e.g. LEDs, Heat Pumps, Variable Speed Drives in freezers etc. All together this might lead to higher levels of harmonics in the distribution grids.

In the short run, it is recommended that DSOs build up knowledge in the field of electromagnetic compatibility, develop emission limits for distorting installations and participate in the standardization work, the latter for the following reasons; Working groups developing standards in the field of electromagnetic compatibility are dominated by manufactures, which involve a high risk that DSOs needs, are not covered sufficiently.

7.3 Grid planning

As this stage it is not feasible to include harmonics from EVs in the grid planning of low-voltage grid due to the imprecise methods to assess harmonics. Roll out of Smart meters or any other sensor devices with harmonic measurement capabilities, could be the first step of including harmonics in grid planning.

8 Conclusion

The focus has been low-voltage grids with households as primary consumption. The method has been chosen and developed in accordance with the EV charging done in installations of the households and with a focus on charging level of 16 A at 230/220 V.

From the analysis, harmonic emissions from EVs is not expected to create a need of reinforcement of the grid in nearest future, however, due to the fact that EVs cannot be assessed separately from other distorting equipment, the topic needs attention as the development of the right standards and assessment methods will take some time.

Moreover, the scope of this report only covers residential areas. The harmonic currents produced by commercial and industrial customers were not taken into account: their effect at MV cannot be neglected.

Sufficient short-circuit level is the most important parameter to avoid harmonic distortion. This should be considered when extending or reinforcing the existing grid, as great improvements can be achieved at relatively low costs.

Furthermore, attention must be paid to harmonic orders of multiple of three as those harmonics are the most significant relative to the limits. Existing methods to assess harmonics are not very accurate, which makes it difficult to include harmonics into grid planning.

Smart meters or any other sensor devices, capable of measuring harmonics, can play a key role in the future for integrating harmonics into the grid planning. A comprehensive collection of data regarding harmonics is very expensive due to the personal costs related to on-site measurements. An evolution of the already existing functionalities related to harmonics of today's smart meters, could provide the required data, in order to include harmonics into future grid planning tools.

Last but not least, a closer cooperation between manufactures and DSOs in the field of electromagnetic compatibility should be established in order to ensure compatibility between equipment connected to the public electricity grids.

9 Appendix

9.1 Derivation of harmonic sources of EV

In this appendix, the derivation of the harmonic sources, used for User dependent (UD)/Timer Based (TB) and the Load Dependent (LD) charging strategy, is described. The harmonic sources of EVs for this analysis are based on the power quality measurements carried out in “D4.2 Recommendation on grid-supporting opportunities of EVs”

Taking into account that EVs connected to the same grid are not the same type of EVs, it is most likely that all chargers are not the same type either. Thus harmonics from different EVs should be considered. Simulation of harmonics is very complex. In order to simplify simulations, the same harmonic source has to be applied to all EVs connected to the grid in the simulations respectively.

In “D4.2 Recommendation on grid-supporting opportunities of EVs”, Power Quality measurements have been carried out on five different EVs (E-car1 – E-car5) at three different charging power levels (P_c).

	E-car1	E-car2	E-car3	E-car4	E-car5
Full	3.0 kW	2.6 kW	3.0 kW	3.0 kW	3.0 kW
Mid	2.6 kW	2.1 kW	2.3 kW	2.5 kW	2.5 kW
Low	2.3 kW	1.3 kW	1.4 kW	1.4 kW	1.4 kW

To consider that different chargers are used in different EVs, an average of the harmonics from all five EVs is calculated for this study.

For the UD and TB strategies, it is assumed that EVs are charging at full power. Thus the harmonic source for UD/TB is an average of the harmonic currents measured at full charging power.

The LD charging strategy requires variable charging power levels, for which reason it cannot be assumed that EVs are charging at full power. Thus the harmonic source for LD is an average, taking into account charging at different power levels. An average including all EVs is calculated for full, mid and low charging power level, after which the maximum value of the three charging power levels is selected for the LD harmonic source.

In the following, the method of deriving the harmonic sources is described:

The harmonic current (in % of I_c) of order (h) from each E-car and charging power level is shown in the following table:

	E-car1			E-car2			E-car3			E-car4			E-car5		
h	Full	Mid	Low	Full	Mid	Low	Full	Mid	Low	Full	Mid	Low	Full	Mid	Low
2	1.47	1.12	1.08	0.33	0.26	1.75	0.15	0.13	0.16	0.28	0.31	0.42	0.23	0.37	0.37
3	6.67	6.62	7.14	3.73	4.38	6.95	12.1	12.5	12.7	7.79	9.25	12.5	6.64	9.45	12.7
4	0.37	0.32	0.24	0.19	0.34	0.59	0.08	0.09	0.12	0.13	0.13	0.22	0.21	0.23	0.24
5	1.42	1.95	1.88	1.98	2.53	4.17	1.25	1.38	1.51	3.06	3.66	5.13	3.78	3.92	4.6
6	0.4	0.28	0.21	0.12	0.12	0.41	0.06	0.12	0.09	0.12	0.15	0.25	0.11	0.17	0.14
7	2.63	2.23	2.74	1.13	1.83	2.84	0.97	1.47	2.12	1.34	1.67	2.67	3.23	3.83	3.32
8	0.32	0.22	0.19	0.1	0.11	0.27	0.07	0.08	0.1	0.09	0.12	0.19	0.11	0.17	0.16
9	2.1	2.13	2.31	1.48	1.8	2.18	1.23	1.88	2.57	1.36	1.01	1.19	0.69	0.75	2.3
10	0.2	0.15	0.17	0.07	0.09	0.21	0.08	0.09	0.09	0.12	0.09	0.12	0.13	0.15	0.11
11	1.35	1.29	1.12	1.03	1.11	1.2	0.9	1.22	1.55	1.08	0.62	1.3	1.06	0.82	1.39
12	0.15	0.13	0.12	0.08	0.11	0.23	0.07	0.11	0.12	0.13	0.1	0.19	0.1	0.09	0.13
13	0.74	1.04	1.29	1.1	1.5	2.06	0.6	0.72	1.09	1.17	1.49	1.03	0.52	1.41	1.09
14	0.15	0.11	0.11	0.09	0.12	0.38	0.09	0.1	0.1	0.1	0.12	0.16	0.1	0.11	0.16
15	0.5	0.65	0.78	0.43	0.7	0.95	0.28	0.37	0.56	0.78	0.62	0.65	0.61	0.58	1.8
16	0.12	0.1	0.09	0.07	0.08	0.24	0.05	0.09	0.08	0.07	0.07	0.11	0.1	0.09	0.14
17	0.52	0.85	0.91	0.47	0.67	0.98	0.44	0.5	0.58	0.43	0.43	0.61	0.72	1.06	0.6
18	0.13	0.08	0.11	0.06	0.07	0.21	0.06	0.08	0.06	0.09	0.08	0.11	0.08	0.12	0.13
19	0.71	0.67	0.6	0.72	0.73	0.93	0.53	0.57	0.69	0.71	0.71	0.62	0.54	1.05	0.52
20	0.16	0.08	0.11	0.06	0.06	0.17	0.07	0.09	0.08	0.06	0.09	0.08	0.11	0.12	0.1
21	0.46	0.47	0.42	0.44	0.55	0.49	0.42	0.41	0.35	0.37	0.37	0.77	0.43	0.61	0.79
22	0.13	0.09	0.1	0.07	0.07	0.15	0.06	0.07	0.08	0.07	0.08	0.1	0.1	0.17	0.1
23	0.46	0.48	0.44	0.49	0.59	0.53	0.46	0.45	0.45	0.29	0.34	0.42	0.28	0.45	0.97
24	0.12	0.08	0.13	0.05	0.09	0.14	0	0.08	0.08	0.07	0.08	0.09	0.08	0.19	0.09
25	0.28	0.44	0.43	0.43	0.44	0.39	0.39	0.36	0.32	0.23	0.44	0.49	0.28	0.3	0.33

In % of I_c.

The average current nominated to one single EV $I_{h,EV}$ [%] is calculated by using the following formulas:

The charging current I_c is calculated for all EVs and charging power levels.

$$I_c = \frac{P_c}{U_n} \cdot 100$$

The harmonic current $I_{h,}$ is calculated for all EVs and charging power levels.

$$I_h = I_h[\%]\frac{I_c}{100}$$

The total harmonic current $I_{h,total}$ is calculated for all five EVs for all charging levels

$$I_{h,total} = \sqrt[\alpha]{I_{h,Ecar1}^{\alpha} + I_{h,Ecar2}^{\alpha} + \cdots + I_{h,Ecar5}^{\alpha}}, where\ \alpha = 1$$

For this study α is set to 1 for the following reasons. In "D4.2 Recommendation on grid-supporting opportunities of EVs" following conclusion has been drawn:

- Harmonics from 3rd to 17th are very close to each other, then an harmonic pollution increment is possible
- Harmonics from 19th to 25th are more equal distributed, in terms of percentage. However these harmonics are characterized by a low amplitude

Additionally the simulations in PowerFactory creates an cancellation effect as the phase angle of the harmonics provided in the simulation is relative to the phase angle of the fundamental current of the EV, which differs for all connection points in the grid. To avoid too optimistic results of the simulations, α is set to 1.

The harmonic current of an average EV $I_{h,EV}$ (in % of I_c) is calculated

$$I_{h,EV}[\%] = \frac{I_{h,total}}{I_{c,Ecar1} + I_{c,Ecar2} + \cdots + I_{Ecar5}} \cdot 100$$

The values adopted for this study can be described as follow:

$$Harmonic\ sources\ UD|TB = [I_{h,EV}\ @Full]$$

$$Harmonic\ sources\ LD = MAX\begin{bmatrix} I_{h,EV}\ @\ Full \\ I_{h,EV}\ @\ Mid \\ I_{h,EV}\ @\ Low \end{bmatrix}$$