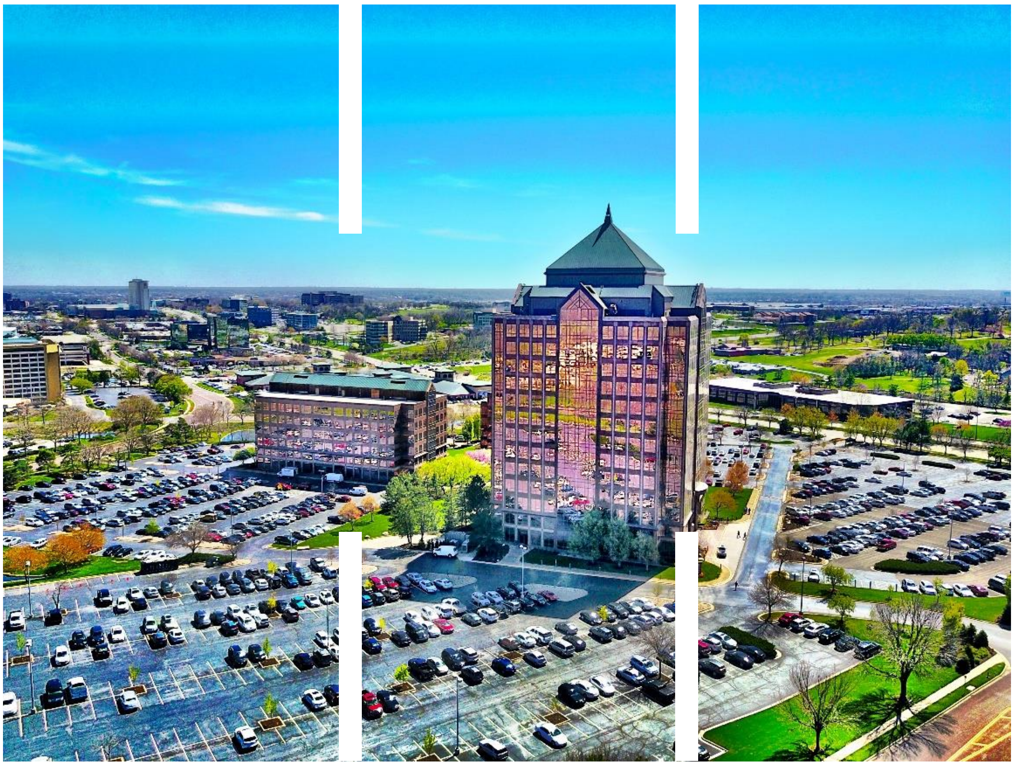

# Western Power Distribution Bristol, UK

## Electric Vehicle Charging

### Monitoring & Analysis

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## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| **ENA** | Electricity Networks Association |
| **EV** | Electric Vehicle |
| **WPD** | Western Power Distribution |
| **POC** | Point of Connection |
| **PCC** | Point of Common Coupling |
| | |
| | |
| | |

# EXECUTIVE SUMMARY

**Purpose and Methodology**

Over the next couple of decades there will be a growing use of electric vehicles (EV) in the United Kingdom, due to government legislation to phase out the use of conventional fossil fuelled private transportation.

The increased use of EV will result in increased loading of the distribution network, whilst the additional use of power electronics to power the charging units will result in higher harmonics being introduced into the power systems.

It should be noted that relevant harmonics caused by electric vehicles is likely to be confidential to the manufacturers and therefore unlikely to be publically available.

There are standards available that cover the limits of harmonic distortion, which have been utilised for this assignment. The relevant standards include IEC 61000-3-2 / IEC 61000-3-12. It should also be noted that where demand is less than 16A, they have unconditional connection to the network.

**Methodology**

For this assignment 23 different vehicles tested, with charge rates from 2.3kW to 7.2kW (10A to 32A). Each vehicle had data taken for 5 different charge cycles with initial charge states ranging from 0 to 90%.

Measurements were made of the 1$^{st}$ to 50$^{th}$ harmonic current for each charge cycle (10 minute averaged), and the 1$^{st}$ to 50$^{th}$ harmonic current measured for each phase, combining some charge cycles (1 second averaged).

**Assessment**

Each vehicle was assessed for compliance against IEC 61000-3-2 and IEC 61000-3-12 standard. This included simultaneous vehicle charging and applicability of exponent, α in IEC 61000-3-6

For each vehicle to determine 'typical' EV harmonic profile, and identify the maximum number of EV that can be simultaneously charged for different network arrangements

**Conclusions**

The measurements show a large spread in the harmonic distortion during charging of different EVs.

For the 7.2kW charge rate, EVs were compliant with IEC 61000-3-12, however this does not grant an unconditional network connection.

There was a very limited number of vehicles at a single PCC, but heavily dependent on method used to determine $Z_h$

Assuming no other load connected, the vehicles distributed along an LV feeder will exceed G5/4 harmonic planning limits before transformer rating is reached.

However, a 11% reduction in PCC source impedance, a 15% reduction in Urban Network maximum source impedance and a 30% reduction in Rural Network maximum source impedance can accommodate maximum number of EVs such that the network harmonic limits are not exceeded before exceeding the respective thermal limits.

# 1 INTRODUCTION

The UK is currently experiencing an exponential growth in the use of electric vehicles (EV) as they become more viable for everyday use [*Ref: http://www.nextgreencar.com/electric-cars/statistics].* The government have also announced that by 2040 they plan to end the sale of all new conventional petrol and diesel cars in the UK to tackle rising air pollution [*Ref: https://www.gov.uk/government/news/plan-for-roadside-no2-concentrations-published*]. This increased reliance on EV places a growing demand on the electricity distribution networks and there are already a number of projects underway investigating how to manage this additional electricity demand [*Ref: Electric Nation, My Electric Avenue, Network Revolution, etc*.].

The use of inverter technology to convert the 50 Hz, AC supply to the DC supply required to charge the electric vehicle also creates a number of potential issues. In particular this conversion can interfere with power quality due to the creation of harmonic currents on the distribution networks. EV should be compliant with the harmonised EU standards under UNECE R10, but various versions of this standard apply to the existing EV fleet and there is further uncertainty over which standards apply due to the transitional provisions of conformity [*Ref: UNECE R10*].

In the UK there are two different requirements that relate to the connection of EV to the power system, chargers capable of supplying less than 16 A and those which can charge at greater than 16 A. Those vehicles that charge at less than 16 A are required to be compliant with IEC 61000-3-2 and compliance with this standard grants unconditional connection to the network *(Ref: IEC 61000-3-2 and unconditional connection statement).* Those vehicles which charge at greater than 16 A (but less than 75A) are required to be compliant with IEC 61000-3-12 but this does not grant unconditional connection to the network. The challenge with electric vehicles is that the vehicle can clearly be plugged in at different locations and therefore impact on the power quality for different sections of the network. Unlike with other technologies where an assessment of the power quality disruption can be made for a specific section of network, a general approach needs to be applied when considering EV. Without understanding the standards that EVs comply to and the impact of their harmonic distortion on the distribution system, customers risk facing increased network charges either due to conservative reinforcement or widespread reactive reinforcement schemes to ensure the network remains within limits.

Western Power Distribution (WPD) have engaged RINA Consulting on this project to carry out the measurement and analysis of the harmonic disturbance of EVs. The project will assess the harmonic disturbance from a number of different EV through repeated charge and discharge tests for a range of vehicles and charging levels on monitored EV charge points. In total 23 different vehicles were tested covering the majority of mainstream vehicles in the UK and incorporating a range of vehicle ages.

The EV vehicle testing took place at the Millbrook Testing Facilities and involved a testing regime that considered a number of charge/discharge cycles for different charge rates and pre-charge conditions. The harmonic distortion of each vehicle is recorded at the individual charge points as well as the collective impact of multiple vehicles at the local distribution transformer.

## 1.1 SCOPE

In order to address the various challenges presented by the predicted large-scale and rapid installation of private and public EV charging points over the next few years, the scope of this project is to investigate the impact of EV on the public distribution network. The scope of works includes the following aspects:

- Specification and installation of power quality measurement equipment
- Determination of background harmonic distortion
- Data acquisition during EV charging

- Harmonic data processing and anonymising
- Harmonic data analysis & modelling
- Presentation of findings

# 2 METHODOLOGY

## 2.1 SPECIFICATION AND INSTALLATION OF POWER QUALITY MEASUREMENT EQUIPMENT

The EV charging was carried out at the Millbrook Testing Ground and in total 23 vehicles were tested covering a range of vehicles available on the UK market. The Millbrook testing ground had 4 single phase charging points installed which were configured across 3 phases supplied from a single distribution transformer.

In order to monitor the harmonic distortion on the power system a number of power quality measurement devices were installed. The device measurement locations were selected to measure both the individual harmonic distortion for the vehicle charging and the combined impact of vehicles charging at the distribution transformer. Figure 2-1 shows the arrangement of the EV charging points and power quality measurement devices listed below:

- 4 x PQube 3, one connected to each vehicle charging point
- 1 x PM7000 Power Quality Analyser
    - 1 connected across all 3 phases supplying the EV charging points

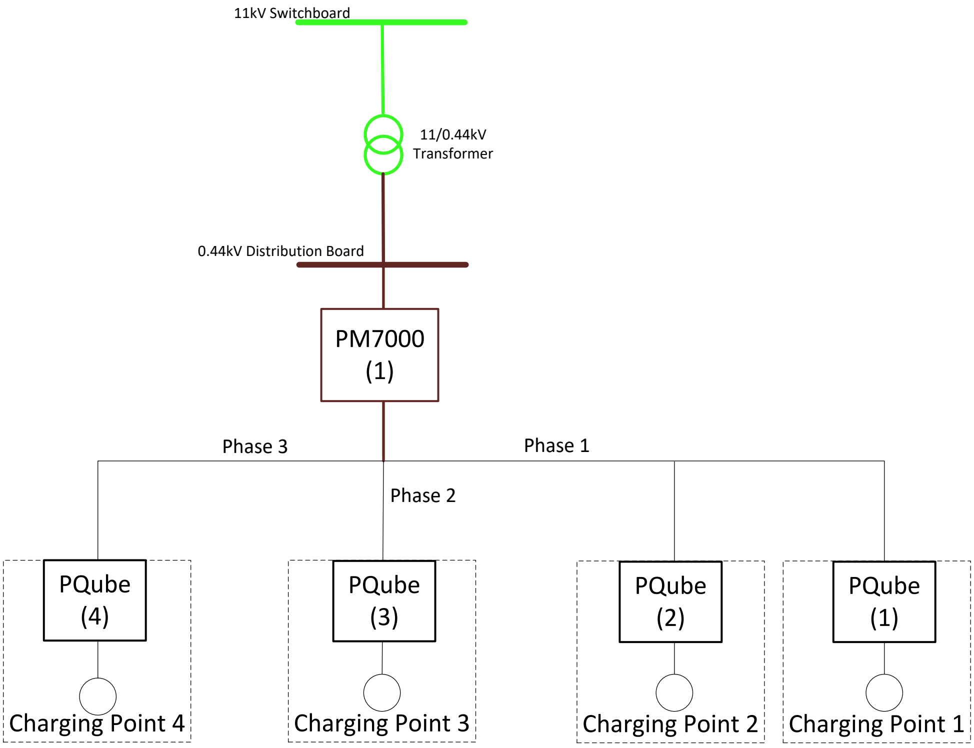


**Figure 2-1: Vehicle charger and power quality measurement device arrangement**

### 2.1.1 PQube 3 Device Settings

The PQube 3 power quality measurement devices were set up to the single phase current supplying each charging point continuously. Each device monitored harmonic voltages and currents up to the 50th harmonic (2.5 kHz) and then provided the averaged value for each 10 minute interval.

To fully analyse the measurements against IEC 61000-3-2 and -12 measurements should only be averaged over a 1.5 second duration. However, due to storage space limitations this was not possible on the PQube devices as they would exceed their storage capacity during some of the vehicle charge cycles. Instead they were left to record continuously with a 10 minute averaging interval and data downloaded for processing every few days. This allowed measurements of both background voltage harmonics and current harmonics during vehicle charging events to be recorded.

### 2.1.2 PM7000 Device Settings

The PM7000 device was connected to monitor all 3 phases that supplied the 4 charging points with charging points 1 and 2 both being connected to the same phase. The device recorded the minimum, mean and maximum harmonic voltage and current distortion up to the 50th harmonic (2.5 kHz) for each phase. The PM7000 was capable of continuously recording the power quality data with 1 second averaging intervals for a duration of 24 hours before its memory capacity was exceeded. Therefore data was downloaded remotely for processing every hour to ensure the memory capacity would not be exceeded.

Since vehicles were not being charged continuously the PM7000 obtained valuable information on the background voltage harmonics on the network. Additionally, because charging points 1 and 2 were both supplied from phase 1, when 2 vehicles were being charged simultaneously this allowed us to investigate how the harmonic currents summated.

## 2.2 DETERMINATION OF BACKGROUND HARMONIC DISTORTION

The PM7000 and PQube devices were installed on the site and set to record continuously from the 1st February 2017 to 23rd July 2017. During this period all vehicle charging events were recorded by the Millbrook proving ground and cross-checked by the current recorded by the power quality devices. This allowed a long period of background harmonic distortion to be recorded from the Millbrook site at the supply point to the vehicle charging points.

This background harmonic distortion can then be used to determine both variations in harmonic distortion over time on the Millbook proving ground. Analysis also allows determination of whether the power supply to the vehicle charging points is compliant with the requirements of IEC 61000-3-2 and -12 when analysing against those standards.

## 2.3 DATA ACQUISTION DURING EV CHARGING

The PQube devices were set to record the averaged harmonic voltage and current over a 10 minute duration whilst the PM7000 recorded the average values over a 1 second duration. Sections 2.1.1 and 2.1.2 provide further details on device settings with regards to monitoring harmonic distortion.

The devices continuously monitor the harmonic voltages and currents at either the individual charging stations or across all three phases supplying the charging points (Figure 2-1). The Millbrook proving ground completed a log for each of the 23 vehicles tested which recorded the following items for each charge cycle:

- Charger ID (1,2,3 or 4)
- Initial state of charge
- Charge rate

- Charge start time
- Charge end time

They also recorded details on the duration and mileage driven to reduce the state of charge from 100% to the level needed for the charge event. However, this information was not relevant to this specific project.

Each vehicle included as part of the test aimed to undergo 5 charge cycles covering 5 different initial states of charge (0 %, 20 %, 40 %, 60 % and 80 %). Some of the vehicles under test were capable of having different charge rates selected and where time allowed additional charge cycles were completed at each charge rate. Vehicles were typically charged at 3.6 or 7.2 kW but some vehicles also allowed charge rates of 2.3 and 6.6 kW. The results of this study have been anonymised so that the harmonic distortion from individual vehicles cannot be identified. However, the following table includes details of the vehicles tested and their charge rates with vehicles listed in alphabetical order and not test order.

**Table 2-1: Manufacturer, model and charge rates of vehicles tested (alphabetical order)**

| Vehicle Make | Vehicle Model | Registration Year | Main Charge Rate (kW) | Additional Charge Rate (kW) |
|---|---|---|---|---|
| BMW | 330e | 2016 | 3.6 | |
| BMW | i3 BEV | 2017 | 7.2 | |
| BMW | i3 REX | 2016 | 7.2 | |
| BMW | i8 | 2016 | 3.6 | |
| Hyundai | Ioniq EV | 2016 | 7.2 | 3.6 |
| Kia | Optima | 2016 | 7.2 | |
| Kia | Soul | 2016 | 7.2 | |
| Kia | Soul | 2017 | 7.2 | |
| Mercedes | B250e | 2017 | 7.2 | |
| Mercedes | C350e | 2016 | 3.6 | |
| Mitsubishi | Outlander Gx4 | 2016 | 3.6 | |
| Nissan | eNV200 | 2016 | 7.2 | |
| Nissan | Leaf Acenta | 2016 | 6.6 | |
| Nissan | Leaf Tekna | 2015 | 7.2 | |
| Peugeot | Ion | 2011 | 3.6 | |
| Renault | Kangoo Mk1 | 2013 | 3.6 | |
| Renault | Kangoo Mk2 | 2014 | 3.6 | |
| Renault | Zoe | 2016 | 7.2 | |
| Tesla | Model S | 2017 | 7.2 | 2.3 |
| Tesla | Model X | 2017 | 7.2 | |
| Volvo | V60 | 2016 | 3.6 | |
| VW | Golf | 2016 | 3.6 | |
| VW | Passat GTE | 2017 | 3.6 | |

## 2.4 HARMONIC DATA PROCESSING AND ANONYMISING

The power quality measurement devices (PQube and PM7000) were setup to record continuously and averaging the data in either 1 second or 10 minute intervals. This data was then downloaded periodically for processing which consisted of the following activities:

- Identifying charge events

- Extracting and categorising the stages of each charge event
- Grouping charge events by vehicle

### 2.4.1 Identifying Charge Events

Initial investigation of the charge current required by each EV showed that once it was connected the charge current rose very rapidly to its expected charging current (within 1 or 2 seconds). As the EV approached its full charge stage the charging current would gradually reduce until eventually the battery was fully charged (Figure 2-2). This typical profile meant that it was possible to determine that a charge event occurred and so it was assumed that an EV was charging whenever the current exceeded 1 A.

Each cycle where the current exceeded 1 A and then eventually reduced back to below 1 A was determined as a charge event. The periods when the current was below 1 A were categorised as background events and used to analyse the background voltage harmonics on the Millbrook network system.

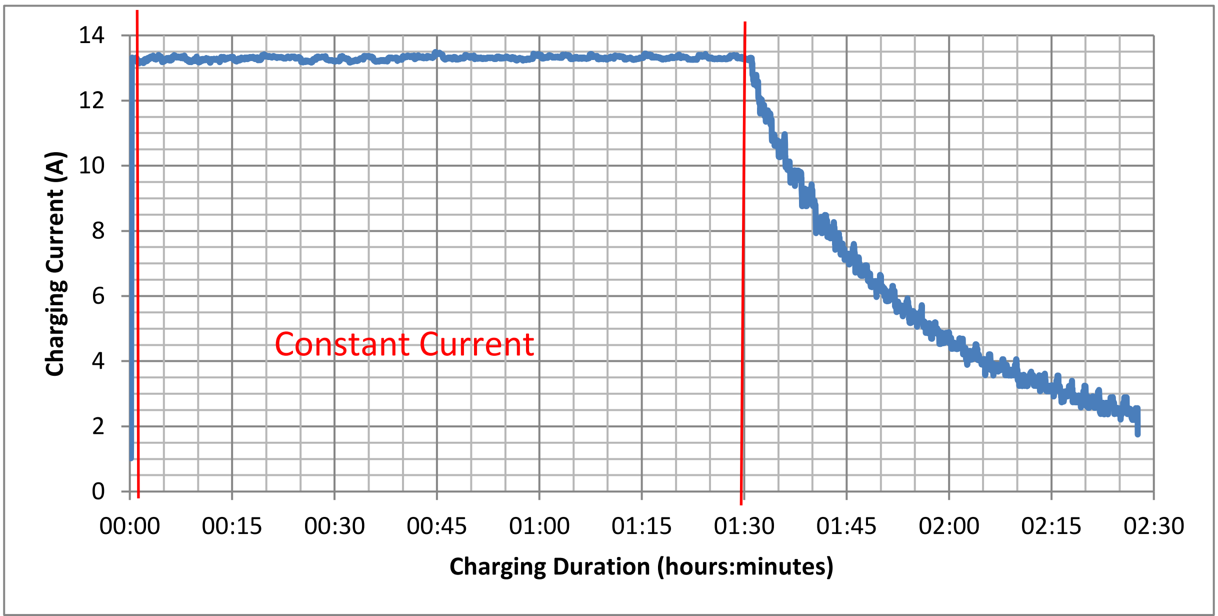


**Figure 2-2: Typical 3.2 kW charging profile with extracted constant current section marked**

### 2.4.2 Extracting and Combining Data for Each Charge Event

As can be seen in Figure 2-2, each charge event has 3 distinct stages:

1. Initial connection and increase in current
2. Constant current period whilst the EV is charged
3. Reducing current as the EV approaches full charge

In discussions and initial review of the results with WPD, it was clear that the biggest concern would be the period when the vehicles were in their constant current phase. This phase has the longest duration and so the possibility of multiple vehicles simultaneously being connected along a single LV feeder is greatest. The subsequent period when the current is reducing has a greater harmonic distortion but the overall magnitude of the harmonic current is lower.

For each charge event the harmonic distortion during the constant current phase was extracted and processed to calculate the mean and maximum harmonic current. In the case of the PQube devices this is the maximum of the 10 minute averaged values and in the case of the PM7000 devices this is the maximum of the maximum values recorded during each 1 second sample period. Similar data analysis was carried out for the reducing current period but that data was not used in the further analysis.

### 2.4.3 Grouping charge events by vehicle

The harmonic data for the constant current period of each charge event was assigned to a specific vehicle. This was achieved through the cross-checking between the start and end times of the recorded charging event and the charge logs provided by Millbrook proving ground. For each vehicle all the charge logs were identified for both the PM7000 and PQube device charging events and grouped together along with details of the initial state of charge and charge rate.

In some cases two vehicles would be simultaneously charged on charging points 1 and 2. These charge events would be recorded individually by the PQube devices but the PM7000 would record the combined impact on phase 1 of these vehicles charging. Further analysis of this simultaneous charging allowed for some initial investigation into the impact of multiple, simultaneous charging events on an LV feeder.

## 2.5 HARMONIC DATA ANALYSIS AND MODELLING

### 2.5.1 Comparison with IEC 61000-3-2 and -12

The harmonic current distortion from each vehicle were tested against the IEC 61000-3-2 and -12 limits and these limits are shown in Table 2-2 and Table 2-3 *[Ref: IEC 61000-3-2, IEC 61000-3-12].* The IEC 61000-3-2 limits only apply to equipment with a load current of less than 16 A per phase and therefore some of the vehicles are not expected to be compliant with this standard. However, compliance with this standard would allow the connection of EV from a power quality perspective to be unconditional and therefore is a good starting point to determine acceptability.

**Table 2-2: Harmonic current emissions for <16 A loads as per IEC 61000-3-2**

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

The harmonic current limits described in IEC 61000-3-12 (Table 2-3) apply to loads with a current of more than 16 A and up to 75A per phase and to which Network Operators do not grant unconditional connection to the power system. Additionally, the specific harmonic current limits that apply depend on the short-circuit ratio ($R_{sce}$) at the connection point with the most stringent being for a $R_{sce}$ of 33. The IEC 61000-3-12 states that ‘any equipment complying with the harmonic current emission limits corresponding to $R_{sce}$ = 33 is suitable for connection at any point of the supply system'. Notwithstanding this, WPD take the view that conditional connection is required and design connections to achieve the assumed $R_{sce}$ value rather than simply allow connection without considering the actual network fault level. Vehicles were tested for compliance against harmonic limits with increasing levels of $R_{sce}$ (33, 66, 120, etc.) until a pass point was reached.

**Table 2-3: Harmonic current emissions for >16 A loads as per IEC 61000-3-12**

| Minimum $R_{sce}$ | Admissible individual harmonic current $I_h/I_{ref}$ [a] % | | | | | | Admissible harmonic parameters % | |
|---|---|---|---|---|---|---|---|---|
| | $I_3$ | $I_5$ | $I_7$ | $I_9$ | $I_{11}$ | $I_{13}$ | $THC/I_{ref}$ | $PWHC/I_{ref}$ |
| 33 | 21,6 | 10,7 | 7,2 | 3,8 | 3,1 | 2 | 23 | 23 |
| 66 | 24 | 13 | 8 | 5 | 4 | 3 | 26 | 26 |
| 120 | 27 | 15 | 10 | 6 | 5 | 4 | 30 | 30 |
| 250 | 35 | 20 | 13 | 9 | 8 | 6 | 40 | 40 |
| ≥350 | 41 | 24 | 15 | 12 | 10 | 8 | 47 | 47 |

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.

[a] $I_{ref}$ = reference current; $I_h$ = harmonic current component.

Since these tests were carried out on the charging points connected to the public distribution network at Millbrook proving ground the background harmonic voltage distortion also needed to be considered. IEC 61000-3-2 and -12 sets out the following limits on the supply voltage being used for the test [*Ref: IEC61000-3-2, IEC 61000-3-12*]:

- Test voltage 230 V ± 0.5 % and 50 Hz ± 2.0 %
- For compliance with IEC 61000-3-2 the harmonic voltage must not exceed the following limits during the test:
  - 0.9 % for harmonic order 3 (2.07 V)
  - 0.4 % for harmonic order 5 (0.92 V)
  - 0.3 % for harmonic order 7 (0.69 V)
  - 0.2 % for harmonic order 9 (0.46 V)
  - 0.2 % for even harmonics of order from 2 to 10 (0.46 V)
  - 0.1 % for harmonics of order from 11 to 40 (0.23 V)
- For compliance with IEC 61000-3-12 the harmonic voltage must not exceed the following limits immediately before and after the test:
  - 1.25 % for harmonic order 3 (2.88 V)
  - 1.5 % for harmonic order 5 (3.45 V)
  - 1.25 % for harmonic order 7 (2.88 V)
  - 0.6 % for harmonic order 9 (1.38 V)
  - 0.7 % for harmonic order 11 (1.61 V)
  - 0.6 % for harmonic order 13 (1.38 V)
  - 0.4 % for even harmonics of order from 2 to 10 (0.92 V)

- 0.3 % for harmonics of order 12 and 14 to 40 (0.69 V)

Initially all vehicles were checked against limits without consideration of the background voltage distortion. For those vehicles which failed, further analysis was carried out to see if the voltage distortion was within the acceptable limits of IEC 61000-3-2 and -12. If it was not then the harmonic current when the harmonic voltage distortion were within acceptable limits were extracted and tested for compliance.

### 2.5.2 Production of Typical Vehicle Harmonic Profile

The harmonic currents were taken for all the vehicles and grouped into those that related to the most common charge rates (3.6 and 7.2 kW). The harmonic current was then averaged to extract both the mean value and the upper quartile value for each harmonic distortion. The latter was used to allow some analysis to be carried out in a situation where vehicles with higher harmonic currents end up becoming the leading vehicle and may effectively reduce the number of vehicles that can be simultaneously charged.

The following four typical harmonic current profiles were produced covering the 1st to 50th harmonic:

1. 3.6 kW EV – Mean
2. 3.6 kW EV – Upper quartile
3. 7.2 kW EV – Mean
4. 7.2 kW EV – Upper quartile

### 2.5.3 Determining the Maximum Number of EVs at a Point of Common Coupling

Taking the typical profiles for the harmonic current distortion of a 3.6 and 7.2 kW EV it is possible to determine the maximum number of vehicles that could be accommodated at a specific point of common coupling (PCC) before the relevant limits are exceeded. The harmonic limits on the distribution network are based on harmonic voltage limits which depend on the harmonic current from the disturbing load along with the impedance at the PCC. WPD were interested in understanding the resulting harmonic voltage distortion based on the impedances from IEC TR 60725 and their own internal standards *[Ref: IEC 60725]* shown in Table 2-4.

**Table 2-4: Reference Impedance**

| Specification | Service Capacity (A) | Reference Source Impedance, $Z_{ref}$ (Ω) | |
|---|---|---|---|
| | | Single Phase | Three Phase |
| IEC TR 60725 | < 100 A | 0.4+0.25j | 0.24+0.15j |
| WPD Design Maximum | < 100 A | 0.22+0.12j | 0.15+0.15j |
| IEC TR 60725 | > 100 A | 0.25+0.25j | 0.15+0.08j |

In determining the maximum number of EVs that can be connected to a single PCC the frequency dependant system impedance ($Z_h$) at the point the harmonic current is injected needs to be calculated. Equation 2-1 shows the equation included in the current version of ENA G5/4-1. However, an alternative equation (2-2) is currently being considered by the ENA G5/4-1 working group and takes into consideration the frequency dependence of the resistive and reactive components separately, this results in a greater sensitivity to higher order harmonics.

To carry out a thorough analysis, calculations were performed and documented for both calculations.

$$Z_h = khZ_1 \qquad (2\text{-}1)$$

$$Z_h = \sqrt{\left(R_1\sqrt{h}\right)^2 + k^2h^2X_1^2} \qquad (2\text{-}2)$$

Where,
$Z_h$ = System impedance at harmonic frequencies

$Z_1$ = Fundamental system impedance ($R_1 + jX_1$)
$k$ = Constant to account for low-order parallel resonance (for LV systems, k = 1 if h ≤ 7, k = 0.5 if h > 7)
$h$ = Harmonic order number

The summation of harmonic currents and voltages also needs to take into consideration the probability of harmonic currents being in phase. The principle applied in G5/4-1 is that harmonic currents connecting at the same node are summed as per IEC 61000-3-6 as shown in equation 2-3. The summation of harmonic voltages as a result of harmonic currents injecting at different points along the network as well as taking into consideration the background harmonic voltage distortion. ENA G5/4-1 assumes that harmonic numbers of 5 or less as well as triplen harmonics are in phase (2-4) and all others are 90 degrees (2-5).

$$V_{hp} = \sqrt[\alpha]{\sum_i V_{hi}^{\alpha}} \quad (2\text{-}3)$$

$$V_{hp} = V_{hm} + V_{hc} \quad (2\text{-}4)$$

$$V_{hp} = \sqrt{V_{hm}^2 + V_{hc}^2} \quad (2\text{-}5)$$

Where,
$V_{hp}$ = Predicted Voltage Harmonic
$V_{hm}$ = Measured Background Voltage Harmonic
$V_{hc}$ = Calculated Equipment Voltage Harmonic

**Table 2-5: IEC 61000-3-6 Summation Exponent [Ref: IEC 61000-3-6]**

| Harmonic Order (h) | α |
|---|---|
| h < 5 | 1 |
| 5 ≤ h ≤ 10 | 1.4 |
| h > 10 | 2 |

In the assessment of the number of vehicles that can be connected to a single PCC the applicable planning limits provided in ENA G5/4 were used (Table 2-6).

Assessments were carried out assuming three different levels of background harmonic voltage distortion; 0, 50% of applicable planning limits and typical values provided by WPD. These values are shown in Table 2-6.

**Table 2-6: Planning Levels for Harmonic Voltages in 400 V Systems [Ref: G5/4]**

| Harmonic Number | Limit (%) | Assumed Background Distortion (%) | | |
|---|---|---|---|---|
| | | 0% | 50% | WPD |
| THD | 5.00 | 0.00 | 2.50 | 1.61 |
| 2 | 1.60 | 0.00 | 0.80 | 0.04 |
| 3 | 4.00 | 0.00 | 2.00 | 0.49 |
| 4 | 1.00 | 0.00 | 0.50 | 0.04 |
| 5 | 4.00 | 0.00 | 2.00 | 2.42 |
| 6 | 0.50 | 0.00 | 0.25 | 0.03 |
| 7 | 4.00 | 0.00 | 2.00 | 1.01 |
| 8 | 0.40 | 0.00 | 0.20 | 0.02 |
| 9 | 1.20 | 0.00 | 0.60 | 0.32 |
| 10 | 0.40 | 0.00 | 0.20 | 0.01 |
| 11 | 3.00 | 0.00 | 1.50 | 0.21 |
| 12 | 0.20 | 0.00 | 0.10 | 0.01 |

| Harmonic Number | Limit (%) | Assumed Background Distortion (%) | | |
|---|---|---|---|---|
| | | 0% | 50% | WPD |
| 13 | 2.50 | 0.00 | 1.25 | 0.16 |
| 14 | 0.20 | 0.00 | 0.10 | 0.01 |
| 15 | 0.30 | 0.00 | 0.15 | 0.18 |
| 16 | 0.20 | 0.00 | 0.10 | 0.01 |
| 17 | 1.60 | 0.00 | 0.80 | 0.11 |
| 18 | 0.20 | 0.00 | 0.10 | 0.01 |
| 19 | 1.20 | 0.00 | 0.60 | 0.12 |
| 20 | 0.20 | 0.00 | 0.10 | 0.01 |
| 21 | 0.20 | 0.00 | 0.10 | 0.06 |
| 22 | 0.20 | 0.00 | 0.10 | 0.01 |
| 23 | 1.20 | 0.00 | 0.60 | 0.06 |
| 24 | 0.20 | 0.00 | 0.10 | 0.01 |
| 25 | 0.70 | 0.00 | 0.35 | 0.06 |
| 26 | 0.20 | 0.00 | 0.10 | 0.01 |
| 27 | 0.66 | 0.00 | 0.33 | 0.03 |
| 28 | 0.20 | 0.00 | 0.10 | 0.01 |
| 29 | 0.63 | 0.00 | 0.32 | 0.03 |
| 30 | 0.20 | 0.00 | 0.10 | 0.01 |
| 31 | 0.60 | 0.00 | 0.30 | 0.03 |
| 32 | 0.20 | 0.00 | 0.10 | 0.00 |
| 33 | 0.20 | 0.00 | 0.10 | 0.02 |
| 34 | 0.20 | 0.00 | 0.10 | 0.00 |
| 35 | 0.56 | 0.00 | 0.28 | 0.02 |
| 36 | 0.20 | 0.00 | 0.10 | 0.00 |
| 37 | 0.54 | 0.00 | 0.27 | 0.02 |
| 38 | 0.20 | 0.00 | 0.10 | 0.00 |
| 39 | 0.20 | 0.00 | 0.10 | 0.01 |
| 40 | 0.20 | 0.00 | 0.10 | 0.00 |
| 41 | 0.50 | 0.00 | 0.25 | 0.01 |
| 42 | 0.20 | 0.00 | 0.10 | 0.00 |
| 43 | 0.49 | 0.00 | 0.25 | 0.01 |
| 44 | 0.20 | 0.00 | 0.10 | 0.00 |
| 45 | 0.20 | 0.00 | 0.10 | 0.01 |
| 46 | 0.20 | 0.00 | 0.10 | 0.00 |
| 47 | 0.47 | 0.00 | 0.24 | 0.01 |
| 48 | 0.20 | 0.00 | 0.10 | 0.00 |
| 49 | 0.46 | 0.00 | 0.23 | 0.01 |
| 50 | 0.20 | 0.00 | 0.10 | 0.00 |

### 2.5.4 Determining the Maximum Number of EVs along a Feeder

In addition to determining the maximum number of EVs that can be connected at a single point of common coupling it is also important to understand the maximum number of EVs that can be simultaneously charged along a single LV feeder. To consider this the impedance at the PCC needs to be understood and this will be dependent on the network type and position along the LV feeder circuit. Table 2-7 shows the minimum and maximum source impedance provided by WPD to assume for each EV connected along an LV feeder.

**Table 2-7: Minimum and maximum source impedance for EV connected along LV feeder**

| Network Type | Impedance at Transformer Secondary Terminals (Ω) | Maximum Source Impedance (Ω) |
|---|---|---|
| Urban | 0.022+0.024j | 0.15+0.08j |
| Rural | 0.053+0.009j | 0.3+0.18j |

As well as the number of vehicles that can be connected along an LV feeder, it is also important to understand how their distribution along the LV feeder impacts on the maximum numbers. Two assessments were carried out to determine the maximum number of vehicles that could be connected along a feeder; firstly with the vehicles equally spaced and secondly with the vehicles randomly distributed. The assessment with the random distributions was repeated 10,000 different times for each number of vehicles and therefore shows the probability that the limits will be exceeded depending on the vehicle distribution.

These assessments were completed as per the assessments described previously (section 2.5.3) and considering the background harmonic voltage distortion levels shown in Table 2-6.

## 2.6 PRESENTATION OF FINDINGS

This project was funded by WPD under the Network Innovation Allowance (NIA) scheme and it is therefore important that the findings of this investigation are widely available to provide a benefit to consumers. In addition to this report there will also be a number of events at which the findings of this work will be available and at the time of writing these include:

- David Mills, "Impact of Electric Vehicle Charging on the Distribution Networks", Celebrating 10 Years of the NGN, Manchester, 9th October 2017
- Simon Ebdon, "EV Emissions Testing", Session: EV Connections and their Network Effects, Low Carbon Networks & Innovation Conference 2017, Telford, 7th December 2017

# 3 RESULTS

This section sets out the harmonic results collected during the project and the initial analysis carried out. More detailed analysis is documented in section 4.

## 3.1 BACKGROUND HARMONIC DISTORTION

The power quality measurement devices were set to continuous record throughout the EV project testing duration and therefore when no EV charging was taking place they were recording background measurements. These background measurements were collected from the 1st February 2017 until the 23rd July 2017. The following three figures present the background harmonic voltage distortion for each phase during each month of the project. To determine this the harmonic voltage measured on the PQube devices was averaged throughout the month for all the periods when no charging took place.

The results show that the background harmonic voltage distortion roughly the same over the 6 month testing period and is similar between the different phases. The voltage distortion during each test was also recorded and used to check compliance with the IEC 61000-3-2 and -12 standards.

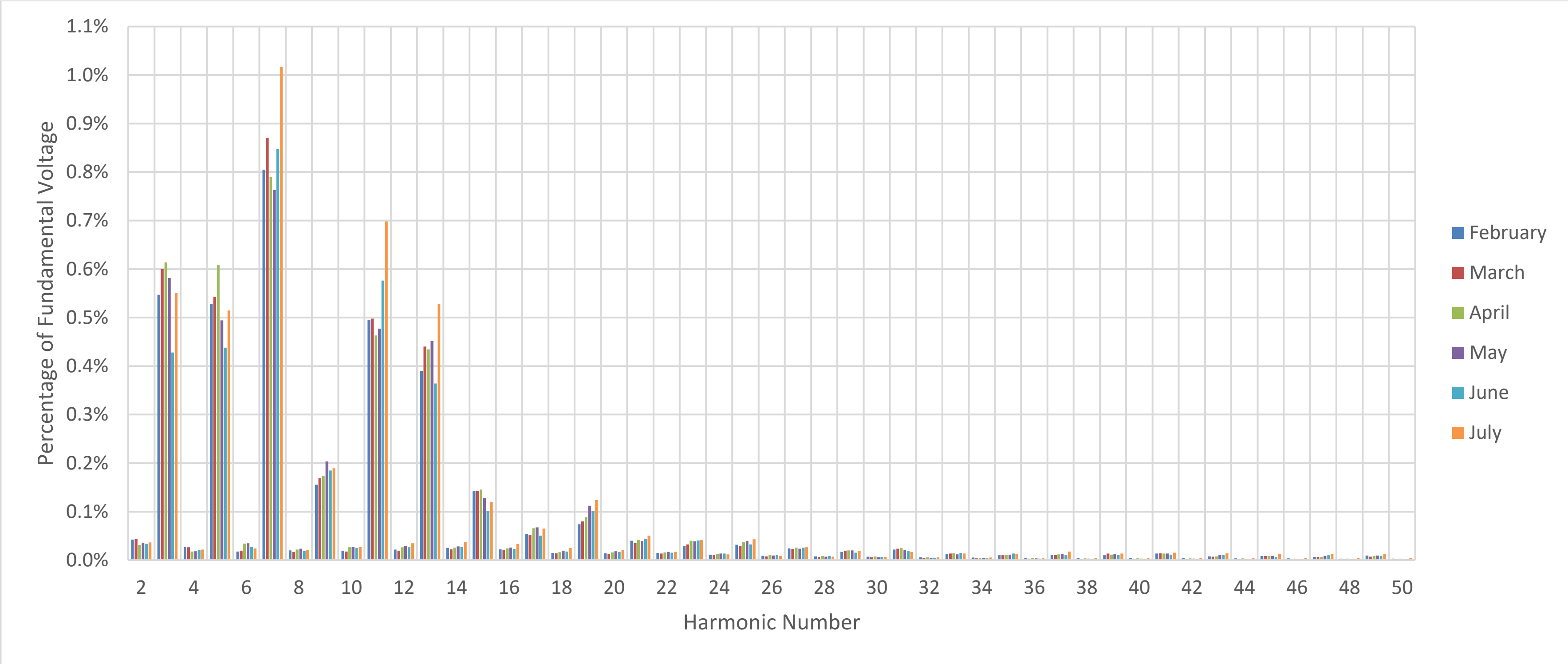


**Figure 3-1: Background harmonic distortion on phase 1 during testing period**

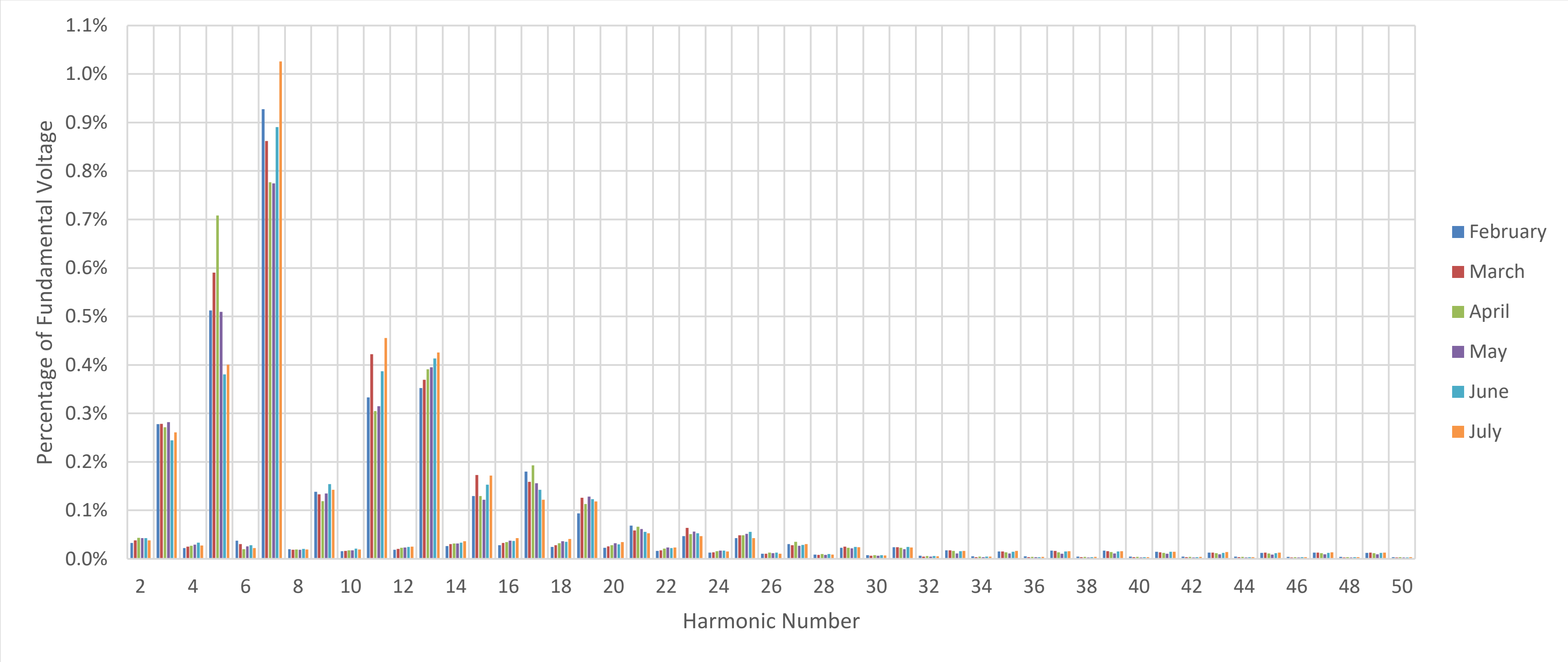


**Figure 3-2: Background harmonic distortion on phase 2 during testing period**

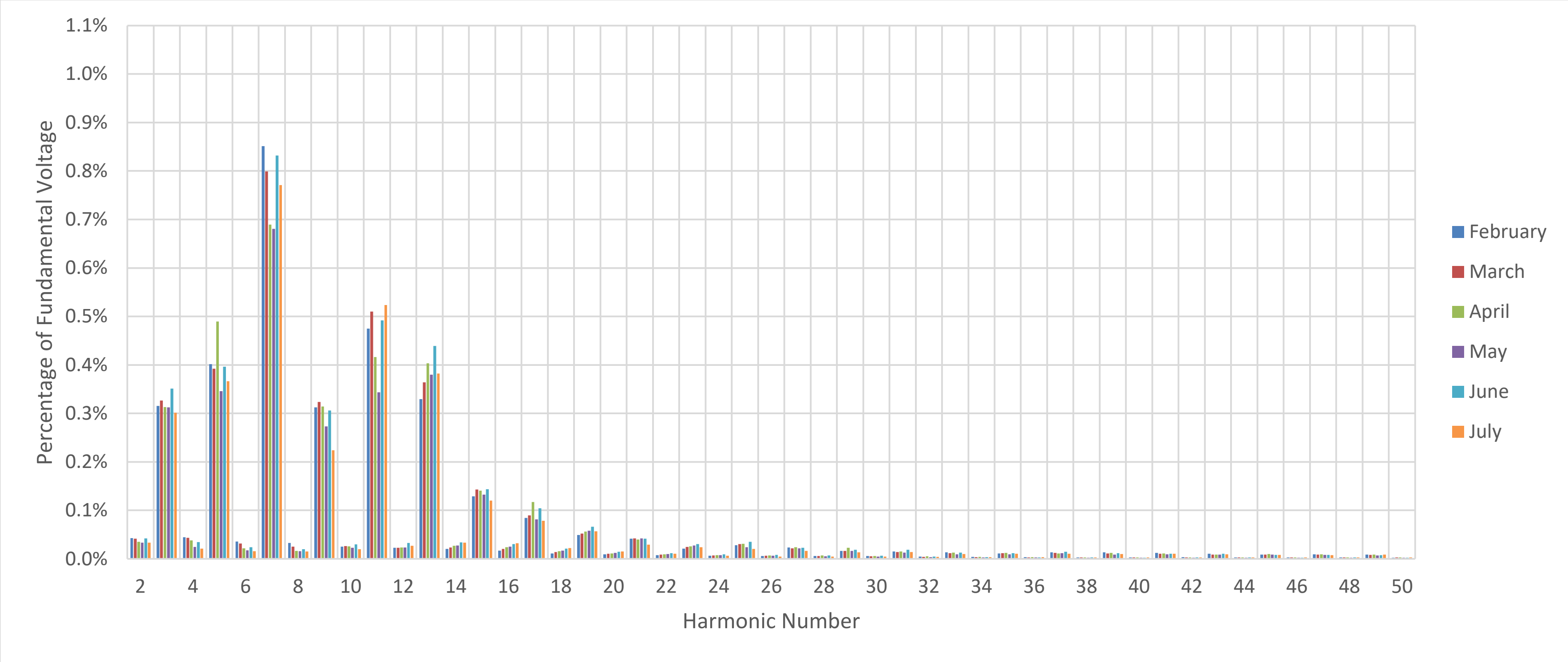


**Figure 3-3: Background harmonic distortion on phase 3 during testing period**

## 3.2 ASSESSMENT AGAINST IEC 61000-3-2 AND -12

### 3.2.1 Initial Assessment

As documented in section 2.3, all 23 vehicles listed in Table 2-1 were tested with a minimum of 5 charge / dis-charge cycles at their default charge rates. Some vehicles also underwent additional testing at other charge rates where conditions allowed. The average harmonic current for each vehicle at each charge rate was assessed against the IEC 61000-3-2 and -12 limits even though vehicles charging at 7.2 kW are not required to comply with the IEC 61000-3-2 standard *[Ref: IEC61000-3-2, Ref: IEC61000-3-12].*

The following tables show the results on the basis of whether the average harmonic current over all of the charge cycles remained within the relevant limits. The vehicles have been anonymised and are listed in no particular order but are separated out into those charging at less than 16 A (Table 3-1) and greater than 16 A (Table 3-2). A short circuit ratio ($R_{sc}$) of 33 and 66 was considered for the IEC 61000-3-12 standard.

**Table 3-1: Assessment of vehicle harmonic current against IEC 61000-3-2 and -12 standards for charge rates <16A**

| Vehicle | Charge Rate (kW) | IEC61000-3-2 | IEC61000-3-12 ($R_{sc}$=33) | IEC61000-3-12 ($R_{sc}$=66) |
|---|---|---|---|---|
| 1 | 3.6 | Pass | Pass | Pass |
| 3 | 3.6 | Pass | Pass | Pass |
| 4 | 3.6 | Fail | Fail | Pass |
| 7 | 3.6 | Pass | Pass | Pass |
| 13 | 3.6 | Pass | Pass | Pass |
| 14 | 3.6 | Pass | Pass | Pass |
| 15 | 3.6 | Pass | Pass | Pass |
| 18 | 3.6 | Pass | Pass | Pass |
| 19 | 3.6 | Fail | Pass | Pass |
| 20 | 3.6 | Fail | Pass | Pass |
| 21a | 2.3 | Pass | Pass | Pass |
| 22a | 3.6 | Fail | Pass | Pass |

**Table 3-2: Assessment of vehicle harmonic current against IEC 61000-3-2 and -12 standards for charge rates >16 A**

| Vehicle | Charge Rate (kW) | IEC61000-3-2 | IEC61000-3-12 ($R_{sc}$=33) | IEC61000-3-12 ($R_{sc}$=66) |
|---|---|---|---|---|
| 2 | 7.2 | Fail | Pass | Pass |
| 5 | 7.2 | Fail | Pass | Pass |
| 6 | 7.2 | Fail | Pass | Pass |
| 8 | 7.2 | Fail | Pass | Pass |
| 9 | 6.6 | Pass | Pass | Pass |
| 10 | 7.2 | Fail | Pass | Pass |
| 11 | 7.2 | Pass | Pass | Pass |
| 12 | 7.2 | Fail | Pass | Pass |
| 16 | 7.2 | Fail | Pass | Pass |
| 21b | 7.2 | Fail | Pass | Pass |
| 22b | 7.2 | Fail | Pass | Pass |
| 23 | 7.2 | Fail | Pass | Pass |
| 24 | 7.2 | Fail | Pass | Pass |

It can be seen in the results that a large number of the vehicles failed when comparing the harmonic current injection against the IEC 61000-3-2 standard. This included some of the 3.6 kW (<16 A) vehicles which would be expected to be compliant with this standard. However, as discussed in section 2.5.1 the standard sets out specific requirements for the harmonic voltage distortion during the test which averaged across all the tests was not achieved. The red fill in the table highlights those vehicles which experienced tests with the power quality of the supply voltage outside of the acceptable IEC 61000-3-2 or -12 limits.

Investigating the background harmonics when no measurements are taking place show that the voltage distortion at the charge points on the Millbrook site is outside of the limits set in IEC 61000-3-2. The following figure compares the average background voltage distortion with the IEC 61000-3-2 and -12 limits.

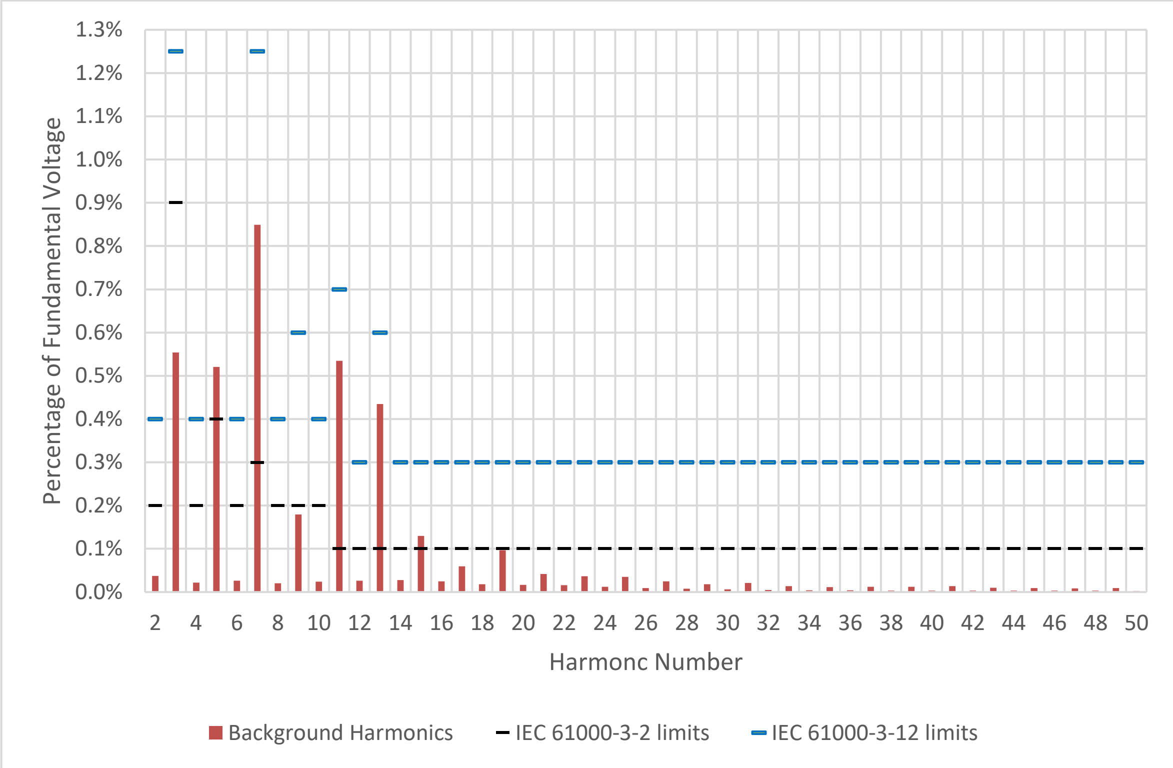


**Figure 3-4: Average background voltage distortion compares against IEC 61000-3-2 and -12 limits**

It is clear that the IEC 61000-3-2 voltage distortion test supply limits are exceeded for the 5th, 7th, 11th, 13th and 15th harmonics and therefore no significant conclusions can be drawn on non-compliance with the IEC 61000-3-2 current limits from those vehicles that exceed the harmonic current limits.

The exceedance is, nevertheless, interesting to note and raises the questions of i) whether non-compliance would have been observed if the voltage distortion test supply limits had been met and ii) noting that background voltage distortion on real networks will exceed that defined for testing against IEC 61000-3-2, whether this may mean that the test specification may be inappropriate or that the current limits may need to be reduced to reflect the increased emissions under higher background voltage distortion found on real networks. It is known that some harmonic current sources act as constant current sources whereas others act as voltage sources behind an impedance and increase current emission if background voltage distortion increases.

Vehicle 4 which has a charge rate of 3.6 kW (<16 A) fails the IEC 61000-3-12 harmonic currents with $R_{sc}$ = 33 but passes with $R_{sc}$ = 66. However, since its demand is less than 16 A it would be expected to pass for all short circuit ratios and therefore further investigation into the failure conditions is needed. Figure 3-5 shows the average harmonic current for each of the charging cycles carried out on vehicle 4 during compared with the IEC 61000-3-2 and -12 harmonic limits (Table 2-2 and Table 2-3). The -12 harmonic limits are shown with a blue line and only extend up to the 13th harmonic and in some cases the limits are greater than the 2.5% upper limit shown in the figure.

The results show that for 5 of the 6 charging cycles the 13th harmonic exceeded the IEC 61000-3-12 $R_{sc}$ = 33, limits. Therefore, this particular vehicle, although having less than 16 A load current, repeatedly produces significant levels of harmonic distortion over multiple charging cycles. This is important to consider when determining the upper limits in the number of vehicles that can connect to a particular system since the spread in harmonic currents can be significant.

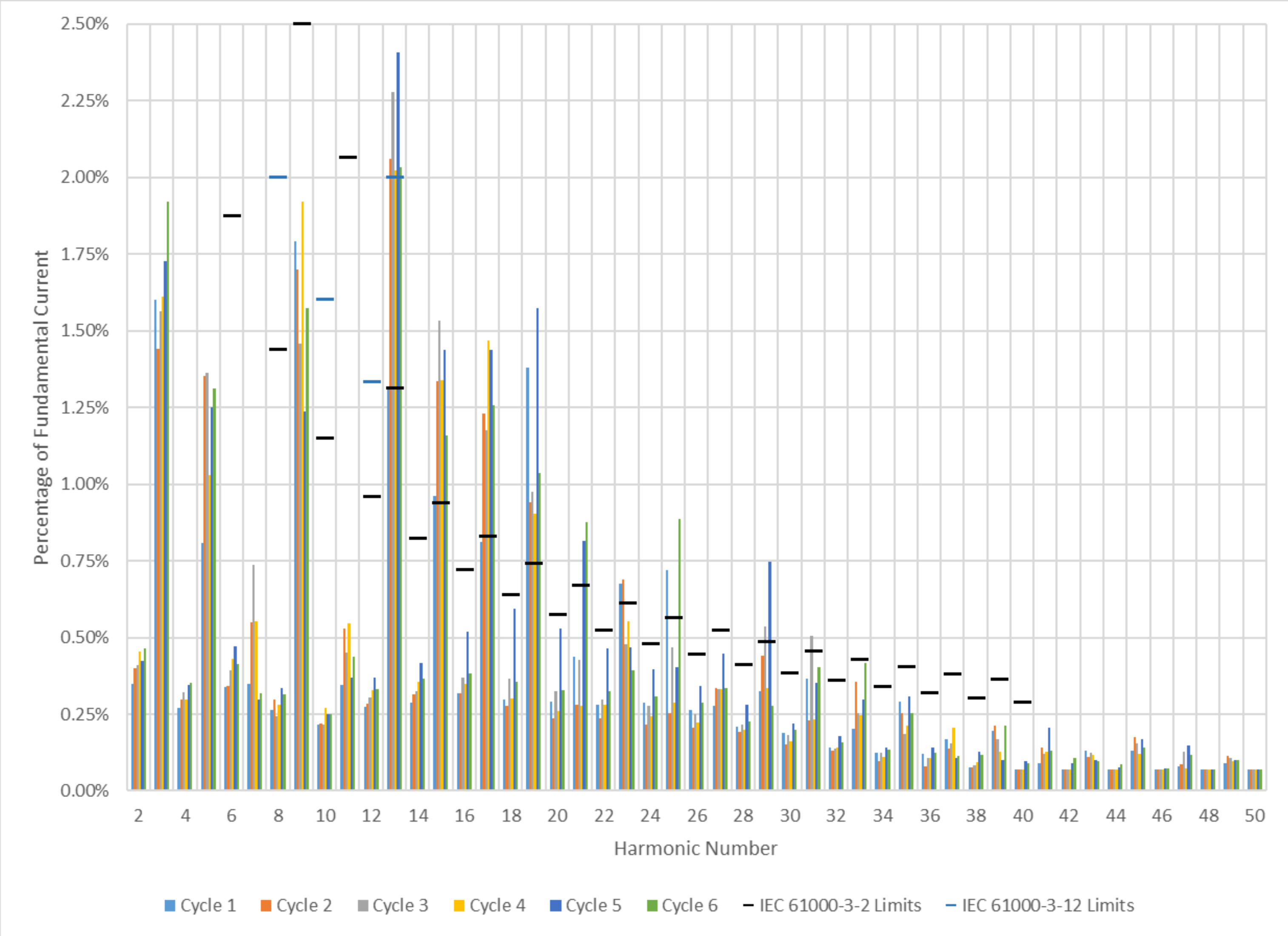


**Figure 3-5: Vehicle 4 harmonic current compared against IEC 61000-3-2 and -12 limits**

## 3.3 TYPICAL EV HARMONIC CURRENT PROFILES

In order to look at representative examples of the number of EVs that can be connected to a particular feeder a typical harmonic current profile for an EV needed to be developed. It was decided that typical profiles should be produced for those vehicles with less than 16 A and greater than 16 A charging rates to represent the different compliance requirements of IEC 61000-3-2 and -12.

To take into consideration the range in harmonic current produced from the vehicles tested 2 profiles were produced for each vehicle charge rate. These covered the median harmonic current from all of the vehicles charged and the upper quartile. Figure 3-6 shows the typical EV profile based on the median of the results and Figure 3-7 for the upper quartile of the measurements.

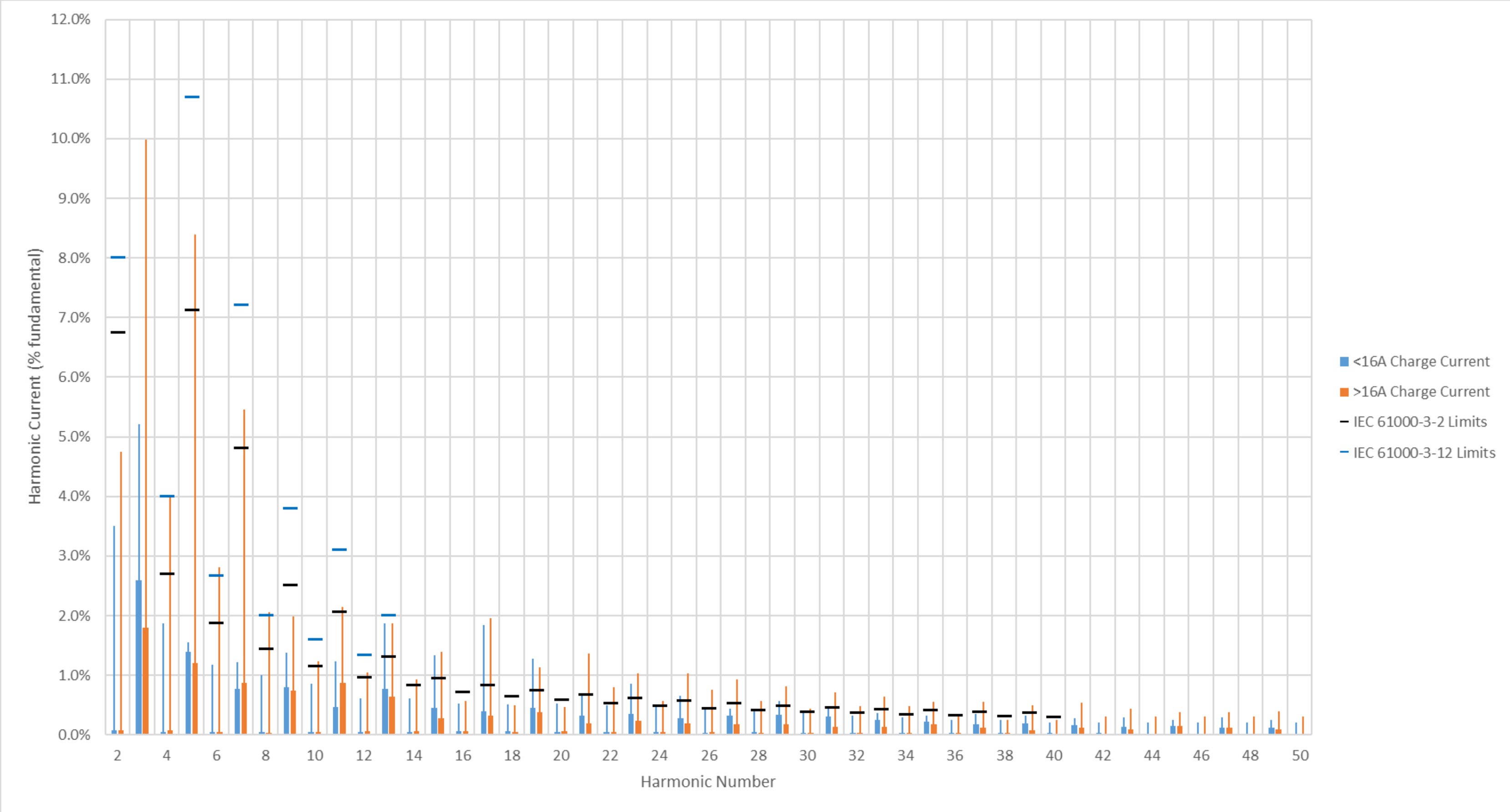


**Figure 3-6: Median typical EV harmonic current assumed for <16 A and >16 A charge currents**

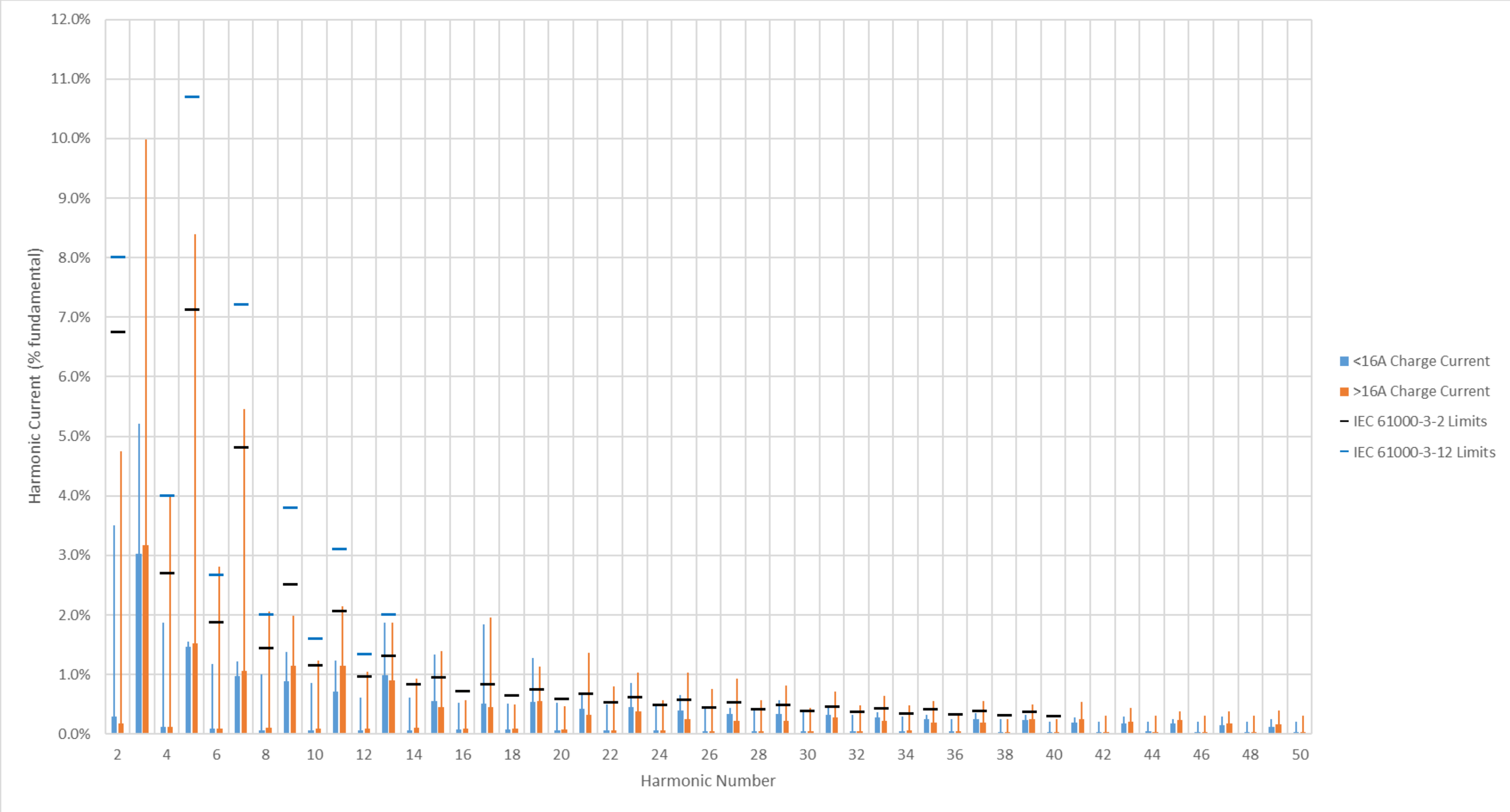


**Figure 3-7: Upper quartile typical EV harmonic current for <16 A and >16 A charging currents**

# 4 ANALYSIS

## 4.1 MAXIMUM NUMBERS OF EVS AT A POINT OF COMMON COUPLING

Taking the typical harmonic current profiles for an EV vehicle detailed in the previous section the maximum number of EVs that can connect to a single PCC was determined. The limits on harmonic voltage distortion are based on ENA G5/4 with the existing or modified calculation of $Z_h$ as documented in section 2.5.3 [*Ref: ENA G5/4, Ref: IEC 61000-3-6]*.

### 4.1.1 Service Capacity < 100 A

The following tables show the maximum number of vehicles that can be connected to a single PCC which has a service capacity of less than 100 A (i.e. one more vehicle and the G5/4 limits are exceeded). These tables just show the maximum number of vehicles from the point of view of power quality and do not take into consideration thermal constraints which may be exceeded first.

**Table 4-1: Maximum number of EVs connected to a PCC with impedance 0.4 + j 0.25Ω**

| $Z_{ref}$ = 0.4+0.25j Ω | ENA ER G5/4 | | | ENA ER G5/4 New $Z_h$ Calculation | | |
|---|---|---|---|---|---|---|
| **Background Harmonic Distortion** | **0%** | **50%** | **WPD** | **0%** | **50%** | **WPD** |
| Median <16A | 2 | 0 | 1 | 6 | 1 | 2 |
| Median >16A | 1 | 0 | 0 | 4 | 1 | 1 |
| Upper Quartile <16A | 1 | 0 | 0 | 4 | 1 | 1 |
| Upper Quartile >16A | 0 | 0 | 0 | 1 | 0 | 0 |

**Table 4-2: Maximum number of EVs connected to a PCC with impedance 0.22 + j 0.12Ω**

| $Z_{ref}$ = 0.22+0.12j Ω | ENA ER G5/4 | | | ENA ER G5/4 New $Z_h$ Calculation | | |
|---|---|---|---|---|---|---|
| **Background Harmonic Distortion** | **0%** | **50%** | **WPD** | **0%** | **50%** | **WPD** |
| Median <16A | 8 | 2 | 4 | 25 | 6 | 11 |
| Median >16A | 5 | 1 | 2 | 16 | 4 | 5 |
| Upper Quartile <16A | 6 | 1 | 2 | 19 | 4 | 6 |
| Upper Quartile >16A | 1 | 0 | 1 | 5 | 1 | 2 |

### 4.1.2 Service Capacity > 100 A

The following table shows the maximum number of vehicles that can be connected to a single PCC which has a service capacity of more than 100 A (i.e. one more vehicle and the G5/4 limits are exceeded). This table just show the maximum number of vehicles from the point of view of power quality and do not take into consideration thermal constraints which maybe exceeded first.

**Table 4-3: Maximum number of EVs connected to a PCC with impedance 0.25 + j 0.25Ω**

| $Z_{ref}$ = 0.25+0.25j Ω | ENA ER G5/4 | | | ENA ER G5/4 New $Z_h$ Calculation | | |
|---|---|---|---|---|---|---|
| Background Harmonic Distortion | 0% | 50% | WPD | 0% | 50% | WPD |
| Median <16A | 4 | 1 | 2 | 7 | 1 | 3 |
| Median >16A | 2 | 0 | 1 | 4 | 1 | 1 |
| Upper Quartile <16A | 3 | 0 | 1 | 5 | 1 | 2 |
| Upper Quartile >16A | 0 | 0 | 0 | 1 | 0 | 0 |

## 4.2 MAXIMUM NUMBERS OF EVS ALONG AN LV FEEDER

An LV feeder could have vehicles connected at different locations and in clusters all of which would impact on the source impedance experienced by the harmonic currents. Therefore the maximum number of EVs that can be connected along a feeder is a range rather than a fixed value depending on their distribution and clustering. To determine this range for each integral of EVs they were randomly distributed between the minimum and maximum source impedance values shown in Table 2-7. This random distribution was repeated a 1000 times and on each occasion the total harmonic voltage distortion on the LV feeder was assessed to determine if it was within the planning limits of G5/4 (Table 2-6). Taking the pass/fail results for all 1000 random distributions a probability of failure could be produced for the different numbers of EVs.

The frequncy dependant calculation of the source impedance was carried out using the alternative calculation for $Z_h$ (equation2-2) since this gives a more realistic representation. Results using the existing calculation of $Z_h$ (equation 2-1) are included in Appendix C.

For the assessment, background harmonic voltage distortion on the LV feeder was assumed to be that provided by WPD for typical background data (Table 2-6). Additionally the thermal limit for each feeder was calculated based on the maximum number of vehicles (3.6 kW or 7.2 kW) that could be charged on the circuit without the source transformer becoming overloaded. This calculation assumes there is no other load connected on the circuit which is clearly unrealistic but gives some indication as to whether the thermal or power quality limits are reached first.

### 4.2.1 Urban Network

The results presented in Figure 4-1 and Figure 4-2 show the number of vehicles at which point the harmonic distortion resulting from the EVs distributed along the feeder exceeds the G5/4 planning limits (assuming WPD measured background harmonic levels). The results are presented for the median and upper quartile EV harmonic profiles to show the impact the spread of vehicle types could have on the system.

The results show that assuming a median EV profile the thermal capability of the circuit is reached before the G5/4 planning limits are exceeded. However, if an upper quartile EV profile is assumed the increased harmonic current means that the number of vehicles that can connect along a feeder is limited by the G5/4 planning limits rather than thermal capability.

There is only a slight reduction in the number of EVs before the G5/4 planning limit is exceeded for the 3.6 kW chargers when the upper quartile profile is used as opposed to the median. However, the number of 7.2 kW charging profile significantly reduces and this is because the upper quartile profile has higher harmonic current at the higher orders (39 and 45 per phase). These higher harmonic orders have low G5/4 planning limits and therefore the limit is exceeded with only a few EVs connected to the feeder.

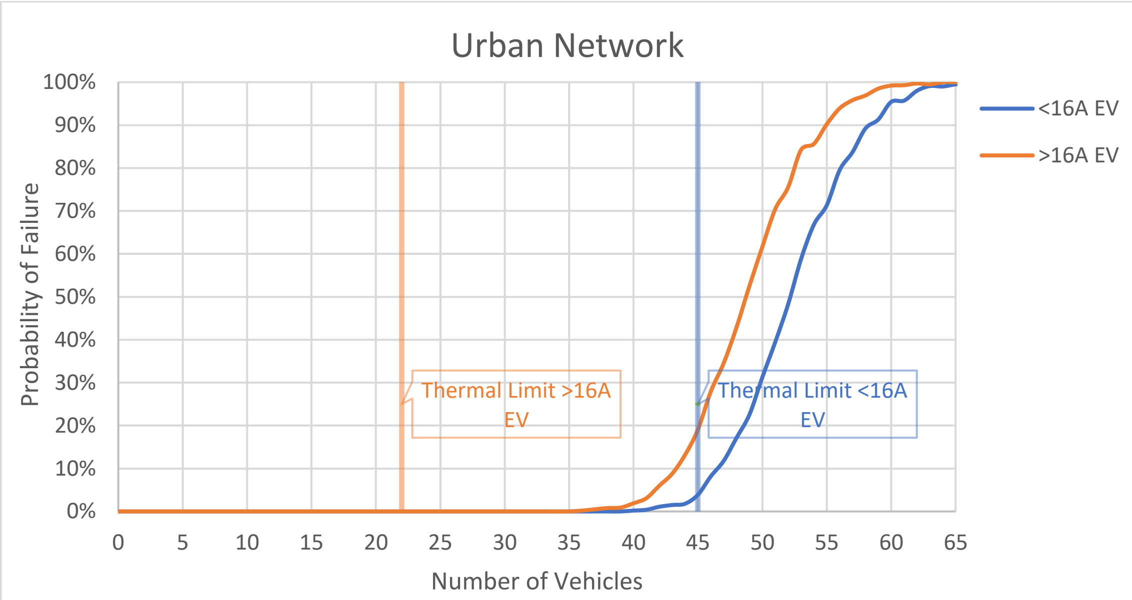


**Figure 4-1: Urban network with median EV profile, WPD background harmonic distortion and $Z_h$ as per equation 2-2**

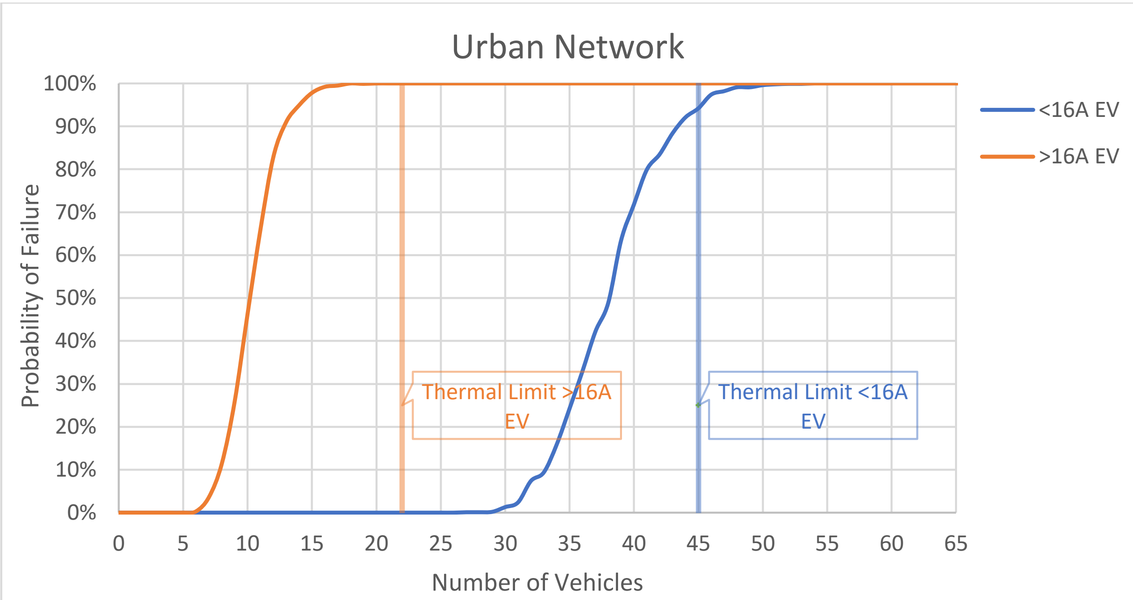


**Figure 4-2: Urban network with upper quartile EV profile, WPD background harmonic distortion and $Z_h$ as per equation 2-2**

### 4.2.2 Rural Network

The results presented in Figure 4-3 and Figure 4-4 show the number of EVs that can be connected on a single feeder in a rural network based on the maximum and minimum impedance data shown in Table 2-7 with the frequency dependence calculated as per equation 2-2. The EVs are randomly distributed along the feeder and assessed against the G5/4 planning limits assuming the typical WPD background harmonic impedance (Table 2-6). The results are presented for the median and upper quartile EV harmonic profiles to show the impact the different vehicle types could have on the system.

The results show that on a rural network with a median EV provide the rating of the source transformer (thermal limit) will be reached before the G5/4 harmonic limits are reached. If the upper quartile harmonic profile is assumed then the G5/4 limits are exceeded with very few EVs connected along the feeder.

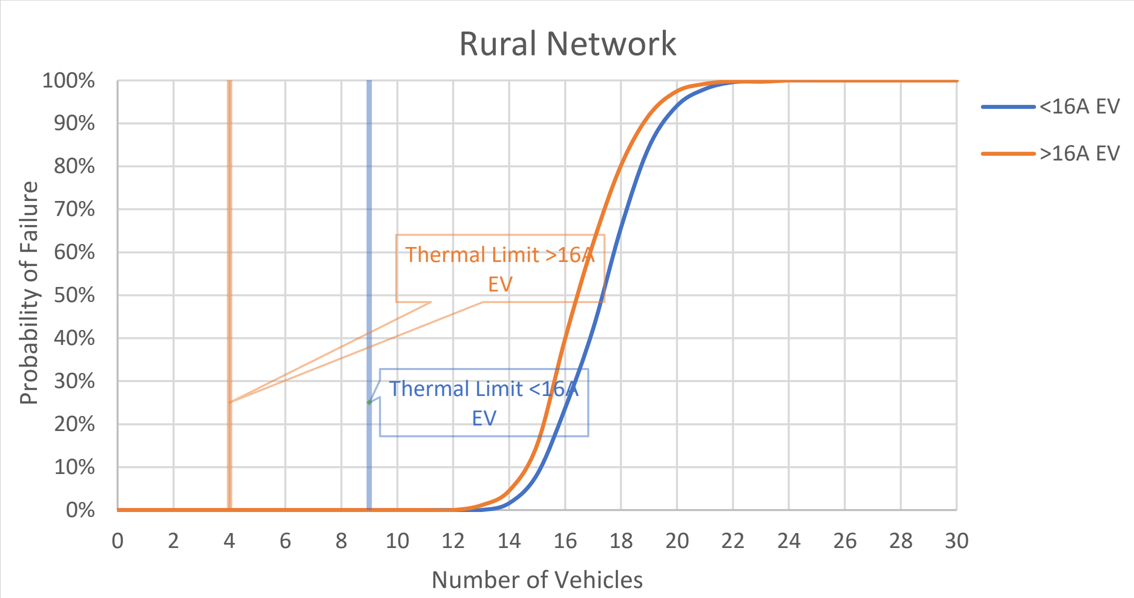


**Figure 4-3: Rural network with typical median EV harmonic current, WPD background harmonic distortion and $Z_h$ calculated as per equation 2-2**

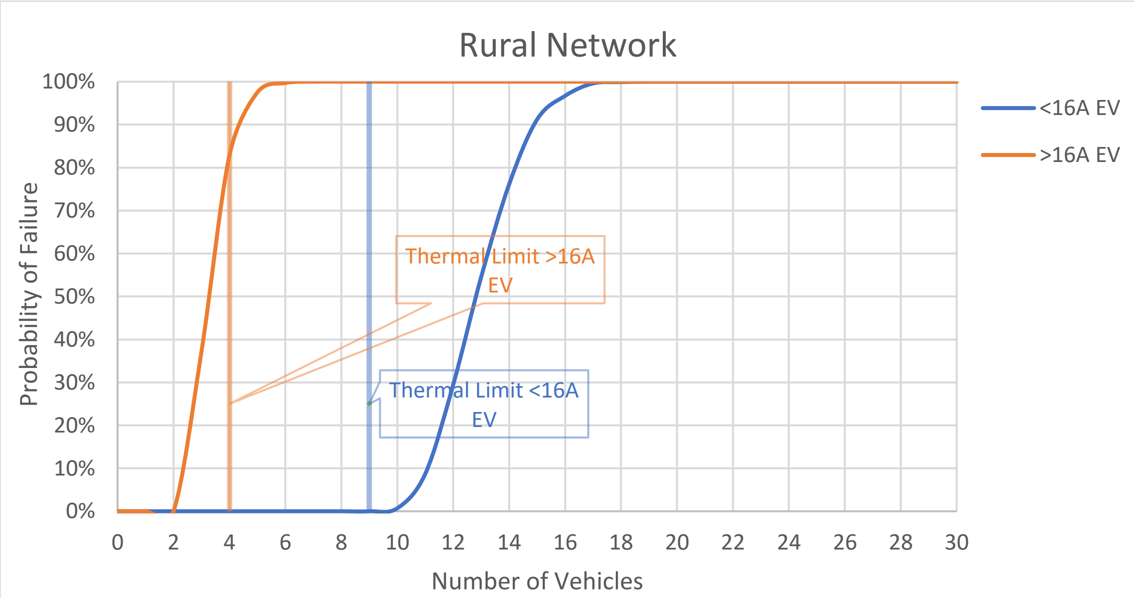


**Figure 4-4: Rural network with typical upper quartile EV harmonic current, WPD background harmonic distortion and $Z_h$ calculated as per equation 2-2**

## 4.3 SOURCE IMPEDANCE ESTIMATION FOR MAXIMUM EV CONNECTION

Further analysis was carried out to estimate the optimal source impedance, for PCC as well as for the Feeder, which can facilitate the maximum number of EVs to be connected, without exceeding the harmonic voltage limits before exceeding the thermal limits.

In the following analysis the source impedance is calculated as per the equation 2-2 only, as this is considered more accurate. Also, the background load at the PCC and the Feeders is not considered.

### 4.3.1 Optimal Source Impedance for PCC (100 A Service)

Table 4-1 and Table 4-2 show various numbers of EVs that can be connected under two different source impedances and various background harmonic content in the network voltage. These were calculated without considering the thermal limits. However, on a 100 A service a maximum of only six 3.7 kW EV chargers (16A) can be connected simultaneously and a maximum of three 7.2 kW chargers can be connected simultaneously, before exceeding the 100 A limit.

From Table 4-1 it can be seen that the most onerous condition is EVs with >16 A charger with Upper Quartile profile under a 50% background harmonic content in the network voltage.

Further simulations were carried out to find the source impedance that can accommodate at least 3 EVs with 7.2 kW charger or at least 6 EVs with 3.6 kW chargers. It was found that a source impedance of **0.196+j0.107 Ω** (an 11% reduction to WPD's source impedance), can satisfy this criteria.

### 4.3.2 Optimal Source Impedance for an Urban Feeder (500 kVA)

The WPD's maximum and minimum source impedances for an Urban Feeder are given in Table 2-7. As observed in section 4.2.1, the 7.2 kW chargers with Upper Quartile harmonic profile lead to violation of harmonic limit before exceeding the thermal limit.

Further simulations were conducted to find the optimal source impedance range that can accommodate the maximum number of EVs, without exceeding the harmonic limits before exceeding the thermal limits. For this analysis only the maximum impedance was varied, while keeping the minimum source impedance the same as the WPD's original value. It was found that an impedance of **0.127+j0.068 Ω**, which is 15% less than WPD's standard maximum impedance, results in a zero probability of violating voltage harmonic limits before exceeding the feeder thermal limit, as shown in Figure 4-5. It should be noted that the number of vehicles (on x-axis) correspond to each phase.

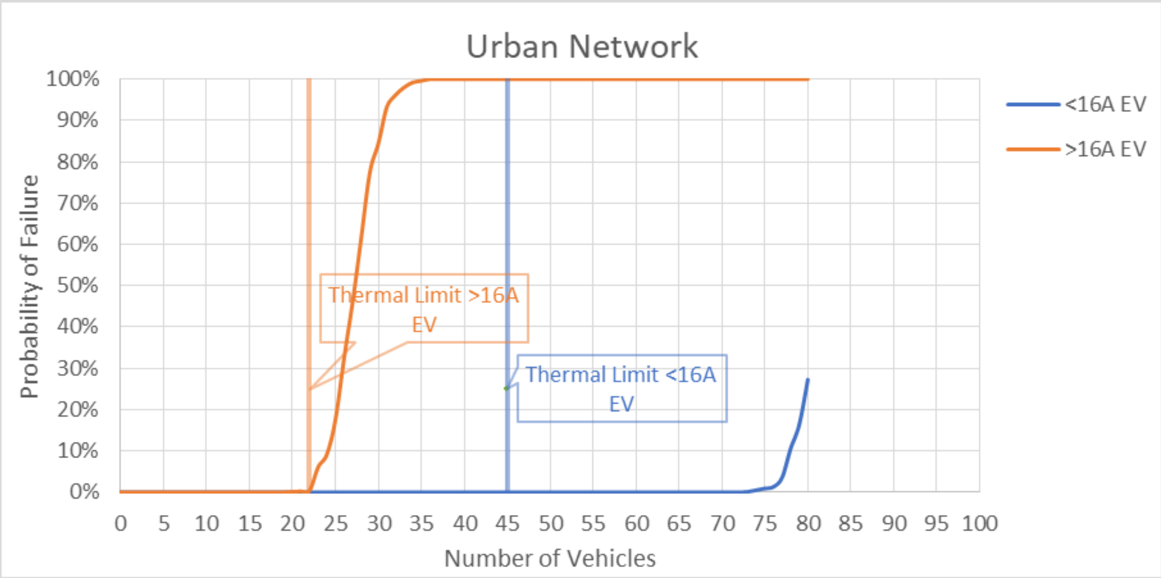


**Figure 4-5: Urban network with a maximum source impedance of 0.127+j0.068 Ω with typical upper quartile EV harmonic current, WPD background harmonic distortion and $Z_h$ calculated as per equation 2-2**

### 4.3.3 Optimal Source Impedance for a Rural Feeder (100 kVA)

The WPD's maximum and minimum source impedances for an Urban Feeder are given in Table 2-7. As observed in section 4.2.2, the 7.2 kW chargers with Upper Quartile harmonic profile leads to violation of harmonic limits before exceeding the thermal limit.

Further simulations were conducted to find the optimal source impedance range that can accommodate the maximum number of EVs, without exceeding the harmonic limits before exceeding the thermal limits. For this analysis only the maximum impedance was varied, while keeping the minimum source impedance the same as the WPD's original value. It was found that an impedance of **0.21+j0.126 Ω**, which is 30% less than WPD's standard maximum impedance, results in a zero probability of violating voltage harmonic limits before exceeding the feeder thermal limit, as shown in Figure 4-6. It should be noted that the number of vehicles (on x-axis) correspond to each phase.

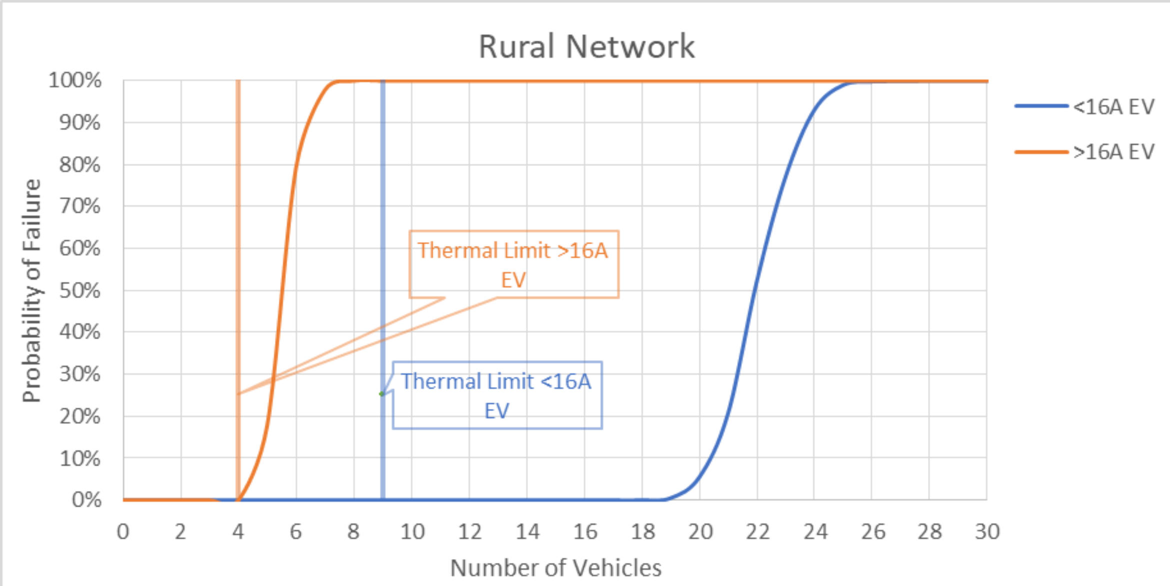


**Figure 4-6: Rural network with a maximum source impedance of 0.21+j0.126 Ω with typical upper quartile EV harmonic current, WPD background harmonic distortion and $Z_h$ calculated as per equation 2-2**

### 4.3.4 Summary of Optimal Source Impedance Results

The above results show that a 15% reduction in Urban Network maximum source impedance and a 30% reduction in Rural Network maximum source impedance can accommodate the maximum number of EVs such that network harmonic limits are not exceeded before exceeding the respective thermal limits. The table below shows the results for the optimal source impedance.

**Table 4-4: Minimum and optimal maximum source impedance for EV connected along LV feeder**

| Network Type | Impedance at Transformer Secondary Terminals (Ω) | Old-Maximum Source Impedance (Ω) | New-Maximum Source Impedance (Ω) |
|---|---|---|---|
| Urban | 0.022+0.024j | 0.15+0.08j | 0.127+j0.068 |
| Rural | 0.053+0.009j | 0.3+0.18j | 0.21+j0.126 Ω |

 

# 5 DISCUSSION AND CONCLUSIONS

**Background Harmonic Distortion**

Whilst carrying out these tests it was important to determine the initial background harmonic distortion at the test site. By taking harmonic measurements during times when no charging events occurred, background harmonic distortion could be determined. The results show that the background harmonic voltage distortion was roughly the same over the 6 month testing period and is similar between the different phases.

The results show that the voltage distortion at the charge points on the Millbrook site is outside of the limits set in IEC 61000-3-2 for test supply voltage distortion.

It is clear that the IEC 61000-3-2 voltage distortion test supply limits are exceeded for the 5th, 7th, 11th, 13th and 15th harmonics and therefore no significant conclusions can be drawn on non-compliance with the IEC 61000-3-2 current limits from those vehicles that exceed the harmonic current limits.

The exceedance is, nevertheless, interesting to note and raises the questions of i) whether non-compliance would have been observed if the voltage distortion test supply limits had been met and ii) noting that background voltage distortion on real networks will exceed that defined for testing against IEC 61000-3-2, whether this may mean that the test specification may be inappropriate or that the current limits may need to be reduced to reflect the increased emissions under higher background voltage distortion found on real networks. It is known that some harmonic current sources act as constant current sources whereas others act as voltage sources behind an impedance and increase current emission if background voltage distortion increases.

**EV Results**

During discussions and initial review of the results with WPD, the biggest concern would be the period when the vehicles were during their constant current phase. This phase has the longest duration and so the possibility of multiple vehicles simultaneously being connected along a single LV feeder is greatest. The subsequent period when the current is reducing has a greater harmonic distortion but the overall magnitude of the harmonic current is lower.

As documented in section 2.3, all 23 vehicles listed in Table 2-1 were tested with a minimum of 5 charge / dis-charge cycles at their default charge rates. Some vehicles also underwent additional testing at other charge rates where conditions allowed. The average harmonic current for each vehicle at each charge rate was assessed against the IEC 61000-3-2 and -12 limits even though vehicles charging at 7.2 kW are not required to comply with the IEC 61000-3-2 standard *[Ref: IEC61000-3-2, Ref: IEC61000-3-12].*

It can be seen in the results that a large number of the vehicles failed when comparing the harmonic current injection against the IEC 61000-3-2 standard. This included some of the 3.6 kW (<16 A) vehicles which would be expected to be compliant with this standard.

Vehicle 4 which has a charge rate of 3.6 kW (<16 A) fails the IEC 61000-3-12 harmonic currents with $R_{sc}$ = 33 but passes with $R_{sc}$ = 66. However, since its demand is less than 16 A it would be expected to pass for all short circuit ratios and therefore further investigation into the failure conditions is suggested. The results show the average harmonic current for each of the charging cycles carried out on vehicle 4 compared with the IEC 61000-3-2 and -12 harmonic limits. The results show that for 5 of the 6 charging cycles the 13th harmonic exceeded the IEC 61000-3-12 $R_{sc}$ = 33, limits. Therefore, this particular vehicle, although having less than 16 A load current, repeatedly produces significant levels of harmonic distortion over multiple charging cycles. This is important to consider when determining the upper limits in the number of vehicles that can connect to a particular system since the spread in harmonic currents can be significant.

**Number of Vehicles Connected at a 100A PCC**

The maximum number of vehicles that can be connected to a single PCC which has a service capacity of less than 100 A (i.e. one more vehicle and the G5/4 limits are exceeded), ranges from 0 to 2 based on ENA ER G5/4

New Zh Calculation, with a PCC impedance of 0.4 + j 0.25Ω, and from 2 to 11 vehicles with a PCC impedance of 0.22 + j 0.12Ω

**Number of Vehicles Connected on a LV Feeder**

An LV feeder could have vehicles connected at different locations and in clusters all of which would impact on the source impedance experienced by the harmonic currents. Therefore the maximum number of EVs that can be connected along a feeder is a range rather than a fixed value depending on their distribution and clustering. The measurements show a large spread in the harmonic distortion during charging of different EVs.

**Number of Vehicles Connected on a LV Feeder on an Urban Network**

The results show the number of vehicles at which point the harmonic distortion resulting from the EVs distributed along the feeder exceeds the G5/4 planning limits (assuming the WPD background harmonic levels). The results are presented for the median and upper quartile EV harmonic profiles to show the impact the different vehicle types could have on the system.

The results show that for both the median and upper quartile EV profile the G5/4 planning limits may be exceeded before the theoretical thermal limit on the circuit is reached. The thermal limit for the 3.6 kW chargers is 44 EVs and outside of the range shown in the graph.

There is only a slight reduction in the number of EVs before the G5/4 planning limit is exceeded for the 3.6 kW chargers when the upper quartile profile is used as opposed to the median. However, the number of 7.2 kW charging profile significantly reduces and this is because the upper quartile profile has higher harmonic current at the higher orders (39 and 45 per phase). These higher harmonic orders have low G5/4 planning limits and therefore the limit is exceed with only a few EVs connected to the feeder.

**Number of Vehicles Connected on a LV Feeder on a Rural Network**

The results show the number of EVs that can be connected on a single feeder in a rural network based on the maximum and minimum impedance data. The EVs are randomly distributed along the feeder and assessed against the G5/4 planning limits assuming the typical WPD background harmonic impedance. The results are presented for the median and upper quartile EV harmonic profiles to show the impact the different vehicle types could have on the system.

The results show that on a rural network with a median EV provide the rating of the source transformer (thermal limit) will be reached before the G5/4 harmonic limits are reached. If the upper quartile harmonic profile is assumed then the G5/4 limits are exceeded with very few EVs connected along the feeder.

**Optimal Source Impedance which can Enable Harmonic Limits are Not Violated before Thermal Limits**

The results show that a 11% reduction in PCC source impedance, a 15% reduction in Urban Network maximum source impedance and a 30% reduction in Rural Network maximum source impedance can accommodate maximum number of EVs such that the network harmonic limits are not exceeded before exceeding the respective thermal limits.

**Overall Conclusion**

For the 7.2 kW charge rate, EVs were compliant with IEC 61000-3-12, however this does not grant an unconditional network connection.

There was a very limited number of vehicles at a single PCC, but heavily dependent on method used to determine $Z_h$.

Assuming no other load connected, the vehicles distributed along an LV feeder will exceed G5/4 harmonic planning limits before transformer rating is reached. However, this problem can be overcome by reducing the maximum source impedance.

# Appendix A EV Harmonic Profiles

**Doc. No. PSE0564001-H1 Rev. 21 –May 2018**

RINA CONSULTING

This appendix includes the typical harmonic current profile for each EV measured during the trial. To ensure the vehicles can be anonymised the vehicles have been presented in no particular order and are grouped into the 3.6 kW and 7.2 kW charge rates.

**Table A-1: Mean harmonic current distortion recorded for each vehicle as a percentage of the fundamental current (vehicles 1 to 11)**

| Harmonic Order | Vehicle Number | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| THD | 1.485% | 1.401% | 1.576% | 1.372% | 1.335% | 1.782% | 1.191% | 1.734% | 1.356% | 1.422% | 1.304% |
| 2 | 0.777% | 0.239% | 0.283% | 0.379% | 0.054% | 0.051% | 0.309% | 0.064% | 0.040% | 0.045% | 0.054% |
| 3 | 5.801% | 1.800% | 3.784% | 1.606% | 0.811% | 2.967% | 2.911% | 0.580% | 0.938% | 0.928% | 2.490% |
| 4 | 0.297% | 0.313% | 0.097% | 0.273% | 0.058% | 0.033% | 0.128% | 0.080% | 0.038% | 0.025% | 0.053% |
| 5 | 1.453% | 2.321% | 0.795% | 1.380% | 0.923% | 1.565% | 1.434% | 0.652% | 1.737% | 1.559% | 5.217% |
| 6 | 0.109% | 0.123% | 0.036% | 0.383% | 0.039% | 0.046% | 0.122% | 0.037% | 0.030% | 0.023% | 0.044% |
| 7 | 1.015% | 0.833% | 0.755% | 0.576% | 1.114% | 1.336% | 0.924% | 1.024% | 0.358% | 0.447% | 1.122% |
| 8 | 0.161% | 0.277% | 0.041% | 0.258% | 0.034% | 0.032% | 0.082% | 0.039% | 0.022% | 0.022% | 0.040% |
| 9 | 0.209% | 1.732% | 0.167% | 1.672% | 0.571% | 0.757% | 0.961% | 0.188% | 0.455% | 0.377% | 0.904% |
| 10 | 0.089% | 0.112% | 0.059% | 0.162% | 0.035% | 0.045% | 0.047% | 0.040% | 0.032% | 0.026% | 0.044% |
| 11 | 1.160% | 0.867% | 0.468% | 0.364% | 1.087% | 0.974% | 0.450% | 0.804% | 0.274% | 0.298% | 0.277% |
| 12 | 0.109% | 0.147% | 0.033% | 0.215% | 0.034% | 0.050% | 0.042% | 0.058% | 0.032% | 0.033% | 0.047% |
| 13 | 1.021% | 1.081% | 0.539% | 2.052% | 0.322% | 0.693% | 0.711% | 0.641% | 0.518% | 0.461% | 0.899% |
| 14 | 0.102% | 0.222% | 0.048% | 0.202% | 0.037% | 0.057% | 0.037% | 0.052% | 0.039% | 0.038% | 0.045% |
| 15 | 0.370% | 0.916% | 0.222% | 1.194% | 0.253% | 0.184% | 0.476% | 0.233% | 0.286% | 0.193% | 0.761% |
| 16 | 0.109% | 0.107% | 0.079% | 0.214% | 0.032% | 0.055% | 0.042% | 0.048% | 0.040% | 0.040% | 0.041% |
| 17 | 0.269% | 0.864% | 0.164% | 1.265% | 0.325% | 0.396% | 0.343% | 0.132% | 0.301% | 0.324% | 0.288% |
| 18 | 0.107% | 0.104% | 0.057% | 0.227% | 0.024% | 0.048% | 0.046% | 0.052% | 0.033% | 0.038% | 0.035% |
| 19 | 0.430% | 0.843% | 0.145% | 1.105% | 0.214% | 0.605% | 0.418% | 0.182% | 0.272% | 0.313% | 0.220% |
| 20 | 0.123% | 0.131% | 0.038% | 0.214% | 0.019% | 0.044% | 0.036% | 0.057% | 0.030% | 0.036% | 0.030% |
| 21 | 0.241% | 0.421% | 0.200% | 0.442% | 0.270% | 0.409% | 0.341% | 0.163% | 0.109% | 0.145% | 0.291% |
| 22 | 0.093% | 0.104% | 0.052% | 0.206% | 0.018% | 0.043% | 0.029% | 0.050% | 0.026% | 0.034% | 0.026% |
| 23 | 0.181% | 0.414% | 0.160% | 0.525% | 0.246% | 0.460% | 0.363% | 0.092% | 0.231% | 0.207% | 0.197% |
| 24 | 0.096% | 0.104% | 0.052% | 0.191% | 0.018% | 0.042% | 0.044% | 0.043% | 0.023% | 0.030% | 0.025% |

| Harmonic Order | Vehicle Number | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 25 | 0.211% | 0.360% | 0.209% | 0.433% | 0.196% | 0.208% | 0.375% | 0.132% | 0.149% | 0.175% | 0.162% |
| 26 | 0.092% | 0.105% | 0.038% | 0.172% | 0.018% | 0.035% | 0.038% | 0.041% | 0.023% | 0.024% | 0.026% |
| 27 | 0.129% | 0.185% | 0.299% | 0.288% | 0.240% | 0.214% | 0.365% | 0.164% | 0.161% | 0.157% | 0.331% |
| 28 | 0.077% | 0.090% | 0.044% | 0.154% | 0.017% | 0.031% | 0.029% | 0.050% | 0.024% | 0.019% | 0.025% |
| 29 | 0.268% | 0.213% | 0.186% | 0.447% | 0.221% | 0.179% | 0.382% | 0.150% | 0.138% | 0.130% | 0.332% |
| 30 | 0.067% | 0.080% | 0.043% | 0.126% | 0.019% | 0.027% | 0.037% | 0.042% | 0.022% | 0.016% | 0.025% |
| 31 | 0.173% | 0.234% | 0.295% | 0.306% | 0.248% | 0.284% | 0.349% | 0.124% | 0.102% | 0.091% | 0.333% |
| 32 | 0.067% | 0.073% | 0.031% | 0.100% | 0.017% | 0.022% | 0.034% | 0.040% | 0.026% | 0.011% | 0.020% |
| 33 | 0.216% | 0.179% | 0.176% | 0.293% | 0.293% | 0.195% | 0.357% | 0.127% | 0.129% | 0.114% | 0.379% |
| 34 | 0.050% | 0.065% | 0.028% | 0.080% | 0.016% | 0.019% | 0.027% | 0.052% | 0.022% | 0.009% | 0.016% |
| 35 | 0.198% | 0.195% | 0.185% | 0.227% | 0.265% | 0.137% | 0.277% | 0.175% | 0.075% | 0.070% | 0.279% |
| 36 | 0.045% | 0.057% | 0.022% | 0.075% | 0.020% | 0.016% | 0.035% | 0.048% | 0.020% | 0.008% | 0.018% |
| 37 | 0.135% | 0.188% | 0.249% | 0.128% | 0.283% | 0.134% | 0.257% | 0.160% | 0.089% | 0.081% | 0.254% |
| 38 | 0.050% | 0.054% | 0.022% | 0.071% | 0.021% | 0.016% | 0.029% | 0.037% | 0.014% | 0.008% | 0.017% |
| 39 | 0.155% | 0.166% | 0.146% | 0.168% | 0.284% | 0.086% | 0.263% | 0.227% | 0.079% | 0.055% | 0.250% |
| 40 | 0.041% | 0.050% | 0.023% | 0.058% | 0.021% | 0.016% | 0.034% | 0.028% | 0.012% | 0.008% | 0.015% |
| 41 | 0.064% | 0.187% | 0.243% | 0.117% | 0.244% | 0.146% | 0.152% | 0.259% | 0.047% | 0.068% | 0.157% |
| 42 | 0.040% | 0.048% | 0.021% | 0.057% | 0.025% | 0.017% | 0.048% | 0.025% | 0.012% | 0.008% | 0.018% |
| 43 | 0.103% | 0.137% | 0.167% | 0.091% | 0.255% | 0.101% | 0.145% | 0.193% | 0.080% | 0.088% | 0.098% |
| 44 | 0.039% | 0.046% | 0.016% | 0.053% | 0.026% | 0.019% | 0.044% | 0.025% | 0.011% | 0.008% | 0.016% |
| 45 | 0.085% | 0.153% | 0.128% | 0.139% | 0.240% | 0.170% | 0.092% | 0.237% | 0.040% | 0.032% | 0.136% |
| 46 | 0.041% | 0.045% | 0.017% | 0.044% | 0.027% | 0.020% | 0.022% | 0.024% | 0.011% | 0.007% | 0.016% |
| 47 | 0.061% | 0.122% | 0.150% | 0.085% | 0.215% | 0.127% | 0.042% | 0.187% | 0.052% | 0.045% | 0.145% |
| 48 | 0.044% | 0.043% | 0.015% | 0.042% | 0.031% | 0.021% | 0.024% | 0.025% | 0.012% | 0.007% | 0.017% |
| 49 | 0.083% | 0.109% | 0.065% | 0.088% | 0.218% | 0.086% | 0.042% | 0.190% | 0.057% | 0.047% | 0.125% |
| 50 | 0.034% | 0.042% | 0.014% | 0.039% | 0.032% | 0.020% | 0.022% | 0.023% | 0.012% | 0.007% | 0.016% |

Table A-2: Mean harmonic current distortion recorded for each vehicle as a percentage of the fundamental current (vehicles 12 to 23)

| Harmonic Order | Vehicle Number | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| THD | 1.739% | 1.349% | 1.557% | 1.371% | 1.376% | 1.463% | 1.357% | 1.473% | 1.392% | 1.388% | 1.471% | 1.259% |
| 2 | 0.077% | 0.065% | 0.050% | 0.062% | 0.796% | 0.070% | 0.532% | 0.192% | 0.086% | 0.129% | 0.286% | 0.077% |
| 3 | 4.736% | 7.734% | 2.619% | 2.540% | 2.414% | 0.720% | 2.674% | 1.280% | 0.557% | 3.596% | 5.871% | 1.181% |
| 4 | 0.043% | 0.028% | 0.026% | 0.041% | 0.255% | 0.028% | 0.087% | 0.185% | 0.086% | 0.071% | 0.150% | 0.052% |
| 5 | 1.203% | 1.733% | 1.361% | 1.479% | 1.068% | 0.319% | 0.397% | 1.085% | 0.499% | 0.778% | 1.497% | 0.854% |
| 6 | 0.049% | 0.040% | 0.015% | 0.042% | 0.320% | 0.039% | 0.054% | 0.169% | 0.053% | 0.068% | 0.175% | 0.048% |
| 7 | 0.828% | 0.628% | 0.337% | 0.280% | 0.877% | 0.290% | 0.949% | 0.723% | 0.616% | 1.084% | 1.193% | 1.336% |
| 8 | 0.049% | 0.028% | 0.018% | 0.022% | 0.210% | 0.030% | 0.048% | 0.144% | 0.041% | 0.063% | 0.138% | 0.048% |
| 9 | 1.140% | 1.212% | 0.745% | 0.745% | 1.412% | 0.466% | 0.370% | 1.578% | 0.268% | 0.747% | 1.151% | 0.951% |
| 10 | 0.060% | 0.034% | 0.020% | 0.022% | 0.223% | 0.027% | 0.041% | 0.149% | 0.044% | 0.070% | 0.108% | 0.058% |
| 11 | 1.358% | 0.456% | 0.123% | 0.164% | 1.308% | 0.361% | 0.827% | 0.720% | 0.613% | 1.198% | 0.739% | 1.173% |
| 12 | 0.075% | 0.036% | 0.021% | 0.029% | 0.172% | 0.029% | 0.049% | 0.150% | 0.057% | 0.072% | 0.102% | 0.068% |
| 13 | 0.853% | 1.190% | 0.600% | 0.750% | 1.287% | 0.241% | 0.454% | 1.411% | 0.740% | 0.540% | 0.940% | 0.505% |
| 14 | 0.081% | 0.039% | 0.023% | 0.039% | 0.172% | 0.033% | 0.059% | 0.166% | 0.058% | 0.079% | 0.129% | 0.077% |
| 15 | 0.282% | 0.615% | 0.451% | 0.576% | 0.788% | 0.202% | 0.341% | 0.981% | 0.274% | 0.457% | 0.438% | 0.452% |
| 16 | 0.087% | 0.040% | 0.022% | 0.043% | 0.159% | 0.031% | 0.065% | 0.180% | 0.060% | 0.078% | 0.119% | 0.081% |
| 17 | 0.213% | 0.322% | 0.448% | 0.522% | 0.530% | 0.335% | 0.558% | 1.069% | 0.198% | 0.865% | 0.385% | 0.747% |
| 18 | 0.079% | 0.034% | 0.017% | 0.037% | 0.156% | 0.031% | 0.069% | 0.173% | 0.058% | 0.071% | 0.099% | 0.076% |
| 19 | 0.379% | 0.373% | 0.501% | 0.557% | 0.591% | 0.230% | 0.283% | 0.992% | 0.291% | 0.599% | 0.493% | 0.450% |
| 20 | 0.072% | 0.036% | 0.016% | 0.035% | 0.122% | 0.038% | 0.060% | 0.183% | 0.060% | 0.067% | 0.083% | 0.073% |
| 21 | 0.156% | 0.136% | 0.335% | 0.301% | 0.211% | 0.203% | 0.492% | 0.573% | 0.191% | 0.768% | 0.186% | 0.639% |
| 22 | 0.058% | 0.032% | 0.016% | 0.027% | 0.101% | 0.035% | 0.056% | 0.181% | 0.053% | 0.059% | 0.075% | 0.065% |
| 23 | 0.188% | 0.090% | 0.448% | 0.391% | 0.333% | 0.221% | 0.372% | 0.491% | 0.119% | 0.623% | 0.222% | 0.556% |
| 24 | 0.044% | 0.025% | 0.017% | 0.023% | 0.094% | 0.035% | 0.054% | 0.165% | 0.051% | 0.054% | 0.059% | 0.059% |
| 25 | 0.190% | 0.139% | 0.359% | 0.306% | 0.247% | 0.187% | 0.479% | 0.528% | 0.174% | 0.568% | 0.207% | 0.525% |
| 26 | 0.036% | 0.020% | 0.014% | 0.020% | 0.105% | 0.036% | 0.050% | 0.145% | 0.041% | 0.051% | 0.052% | 0.053% |

| Harmonic Order | Vehicle Number | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 27 | 0.164% | 0.170% | 0.338% | 0.304% | 0.260% | 0.208% | 0.527% | 0.357% | 0.188% | 0.538% | 0.137% | 0.481% |
| 28 | 0.034% | 0.017% | 0.012% | 0.016% | 0.199% | 0.042% | 0.057% | 0.139% | 0.037% | 0.049% | 0.046% | 0.048% |
| 29 | 0.090% | 0.130% | 0.337% | 0.311% | 0.314% | 0.151% | 0.386% | 0.343% | 0.147% | 0.414% | 0.173% | 0.349% |
| 30 | 0.031% | 0.015% | 0.012% | 0.014% | 0.195% | 0.041% | 0.044% | 0.121% | 0.033% | 0.047% | 0.040% | 0.042% |
| 31 | 0.105% | 0.191% | 0.233% | 0.189% | 0.317% | 0.144% | 0.522% | 0.345% | 0.117% | 0.426% | 0.132% | 0.392% |
| 32 | 0.029% | 0.015% | 0.009% | 0.011% | 0.275% | 0.030% | 0.045% | 0.114% | 0.046% | 0.044% | 0.035% | 0.035% |
| 33 | 0.072% | 0.143% | 0.287% | 0.239% | 0.237% | 0.171% | 0.497% | 0.264% | 0.121% | 0.325% | 0.111% | 0.265% |
| 34 | 0.025% | 0.013% | 0.008% | 0.011% | 0.218% | 0.027% | 0.044% | 0.094% | 0.062% | 0.042% | 0.032% | 0.032% |
| 35 | 0.067% | 0.131% | 0.227% | 0.214% | 0.176% | 0.125% | 0.425% | 0.194% | 0.198% | 0.345% | 0.115% | 0.290% |
| 36 | 0.025% | 0.012% | 0.008% | 0.010% | 0.154% | 0.031% | 0.039% | 0.084% | 0.054% | 0.041% | 0.030% | 0.029% |
| 37 | 0.102% | 0.176% | 0.183% | 0.156% | 0.109% | 0.145% | 0.484% | 0.163% | 0.221% | 0.325% | 0.106% | 0.263% |
| 38 | 0.023% | 0.012% | 0.007% | 0.010% | 0.078% | 0.035% | 0.040% | 0.075% | 0.036% | 0.042% | 0.028% | 0.028% |
| 39 | 0.056% | 0.104% | 0.196% | 0.179% | 0.071% | 0.119% | 0.360% | 0.211% | 0.287% | 0.310% | 0.078% | 0.247% |
| 40 | 0.022% | 0.013% | 0.007% | 0.011% | 0.045% | 0.035% | 0.041% | 0.071% | 0.028% | 0.041% | 0.026% | 0.027% |
| 41 | 0.084% | 0.092% | 0.120% | 0.147% | 0.043% | 0.114% | 0.355% | 0.158% | 0.294% | 0.331% | 0.067% | 0.290% |
| 42 | 0.021% | 0.013% | 0.008% | 0.010% | 0.031% | 0.029% | 0.040% | 0.069% | 0.027% | 0.038% | 0.024% | 0.026% |
| 43 | 0.070% | 0.131% | 0.133% | 0.113% | 0.033% | 0.131% | 0.328% | 0.210% | 0.239% | 0.253% | 0.075% | 0.197% |
| 44 | 0.020% | 0.013% | 0.006% | 0.010% | 0.022% | 0.027% | 0.046% | 0.068% | 0.027% | 0.035% | 0.023% | 0.024% |
| 45 | 0.064% | 0.099% | 0.147% | 0.154% | 0.033% | 0.080% | 0.252% | 0.180% | 0.261% | 0.236% | 0.066% | 0.219% |
| 46 | 0.020% | 0.013% | 0.007% | 0.010% | 0.019% | 0.025% | 0.042% | 0.060% | 0.026% | 0.034% | 0.022% | 0.023% |
| 47 | 0.049% | 0.100% | 0.107% | 0.108% | 0.023% | 0.092% | 0.267% | 0.134% | 0.217% | 0.168% | 0.059% | 0.177% |
| 48 | 0.019% | 0.013% | 0.008% | 0.010% | 0.018% | 0.022% | 0.040% | 0.055% | 0.026% | 0.033% | 0.022% | 0.023% |
| 49 | 0.036% | 0.135% | 0.124% | 0.110% | 0.032% | 0.106% | 0.229% | 0.164% | 0.202% | 0.125% | 0.054% | 0.148% |
| 50 | 0.018% | 0.013% | 0.007% | 0.010% | 0.017% | 0.023% | 0.051% | 0.052% | 0.025% | 0.032% | 0.022% | 0.022% |

# Appendix B Typical EV Data

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The following shows the data used to represent a typical EV harmonic current injection for vehicles with a charge rate equivalent of less than and greater than 16 A. Typical vehicles were assessed assuming the median and upper quartile of the measured harmonic current with the maximum included to show the highest value.

The cells with red text represent those values that exceed the IEC 61000-3-2 or IEC 61000-3-12 limits as appropriate. The results clearly show that for either the median or upper quartile typical vehicle profiles none of the harmonic currents exceeded the requirements of the applicable standards. Figure 3-6 and Figure 3-7 show these results graphically.

**Table 5-3: Harmonic currents assumes to represent typical EVs**

| Harmonic Number | Harmonic Currents as % of Fundamental | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | IEC 61000-3-2 | IEC 61000-3-12 | <16A Charge Current | | | >16A Charge Current | | |
| | | | Median | Upper Quartile | Maximum | Median | Upper Quartile | Maximum |
| 2 | 6.75% | 8.00% | 0.08% | 0.29% | 3.50% | 0.08% | 0.18% | 4.75% |
| 3 | 14.38% | 21.60% | 2.59% | 3.03% | 5.21% | 1.80% | 3.17% | 9.98% |
| 4 | 2.69% | 4.00% | 0.05% | 0.11% | 1.88% | 0.07% | 0.12% | 4.00% |
| 5 | 7.13% | 10.70% | 1.39% | 1.46% | 1.55% | 1.20% | 1.53% | 8.40% |
| 6 | 1.88% | 2.67% | 0.05% | 0.10% | 1.18% | 0.05% | 0.10% | 2.81% |
| 7 | 4.81% | 7.20% | 0.76% | 0.98% | 1.22% | 0.88% | 1.05% | 5.46% |
| 8 | 1.44% | 2.00% | 0.04% | 0.07% | 1.01% | 0.04% | 0.10% | 2.06% |
| 9 | 2.50% | 3.80% | 0.80% | 0.89% | 1.38% | 0.75% | 1.15% | 1.98% |
| 10 | 1.15% | 1.60% | 0.05% | 0.06% | 0.86% | 0.04% | 0.09% | 1.23% |
| 11 | 2.06% | 3.10% | 0.47% | 0.71% | 1.23% | 0.87% | 1.14% | 2.14% |
| 12 | 0.96% | 1.33% | 0.05% | 0.06% | 0.61% | 0.06% | 0.09% | 1.05% |
| 13 | 1.31% | 2.00% | 0.78% | 0.98% | 1.87% | 0.64% | 0.90% | 1.86% |
| 14 | 0.82% | - | 0.05% | 0.07% | 0.61% | 0.07% | 0.10% | 0.93% |
| 15 | 0.94% | - | 0.46% | 0.56% | 1.33% | 0.28% | 0.45% | 1.39% |
| 16 | 0.72% | - | 0.06% | 0.08% | 0.53% | 0.06% | 0.10% | 0.56% |
| 17 | 0.83% | - | 0.39% | 0.51% | 1.84% | 0.33% | 0.46% | 1.95% |
| 18 | 0.64% | - | 0.06% | 0.07% | 0.51% | 0.05% | 0.09% | 0.50% |
| 19 | 0.74% | - | 0.45% | 0.54% | 1.27% | 0.38% | 0.56% | 1.14% |
| 20 | 0.58% | - | 0.04% | 0.07% | 0.53% | 0.06% | 0.08% | 0.47% |
| 21 | 0.67% | - | 0.33% | 0.43% | 0.70% | 0.19% | 0.32% | 1.36% |
| 22 | 0.52% | - | 0.05% | 0.06% | 0.49% | 0.05% | 0.07% | 0.80% |
| 23 | 0.61% | - | 0.35% | 0.45% | 0.85% | 0.23% | 0.37% | 1.03% |
| 24 | 0.48% | - | 0.05% | 0.05% | 0.49% | 0.04% | 0.06% | 0.56% |
| 25 | 0.56% | - | 0.27% | 0.39% | 0.65% | 0.20% | 0.25% | 1.04% |
| 26 | 0.44% | - | 0.04% | 0.05% | 0.44% | 0.04% | 0.05% | 0.75% |
| 27 | 0.52% | - | 0.32% | 0.34% | 0.44% | 0.18% | 0.22% | 0.93% |
| 28 | 0.41% | - | 0.04% | 0.05% | 0.40% | 0.04% | 0.05% | 0.56% |
| 29 | 0.48% | - | 0.33% | 0.33% | 0.57% | 0.17% | 0.22% | 0.82% |
| 30 | 0.38% | - | 0.04% | 0.04% | 0.36% | 0.03% | 0.04% | 0.44% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 31 | 0.45% | - | 0.30% | 0.32% | 0.49% | 0.13% | 0.27% | 0.71% |
| 32 | 0.36% | - | 0.03% | 0.04% | 0.33% | 0.03% | 0.04% | 0.48% |
| 33 | 0.43% | - | 0.26% | 0.28% | 0.37% | 0.13% | 0.22% | 0.64% |
| 34 | 0.34% | - | 0.03% | 0.05% | 0.30% | 0.03% | 0.06% | 0.48% |
| 35 | 0.40% | - | 0.22% | 0.25% | 0.33% | 0.17% | 0.19% | 0.55% |
| 36 | 0.32% | - | 0.03% | 0.04% | 0.25% | 0.03% | 0.05% | 0.32% |
| 37 | 0.38% | - | 0.18% | 0.24% | 0.34% | 0.12% | 0.20% | 0.55% |
| 38 | 0.30% | - | 0.03% | 0.04% | 0.25% | 0.03% | 0.04% | 0.25% |
| 39 | 0.36% | - | 0.20% | 0.24% | 0.33% | 0.08% | 0.25% | 0.49% |
| 40 | 0.29% | - | 0.03% | 0.04% | 0.20% | 0.02% | 0.03% | 0.25% |
| 41 | - | - | 0.16% | 0.20% | 0.28% | 0.12% | 0.25% | 0.55% |
| 42 | - | - | 0.03% | 0.04% | 0.20% | 0.02% | 0.03% | 0.31% |
| 43 | - | - | 0.14% | 0.18% | 0.29% | 0.09% | 0.21% | 0.44% |
| 44 | - | - | 0.03% | 0.04% | 0.20% | 0.02% | 0.03% | 0.31% |
| 45 | - | - | 0.15% | 0.17% | 0.25% | 0.15% | 0.24% | 0.38% |
| 46 | - | - | 0.02% | 0.04% | 0.20% | 0.02% | 0.03% | 0.31% |
| 47 | - | - | 0.12% | 0.15% | 0.29% | 0.12% | 0.18% | 0.38% |
| 48 | - | - | 0.02% | 0.03% | 0.21% | 0.02% | 0.03% | 0.31% |
| 49 | - | - | 0.12% | 0.12% | 0.25% | 0.10% | 0.16% | 0.39% |
| 50 | - | - | 0.02% | 0.03% | 0.21% | 0.02% | 0.03% | 0.31% |

# Appendix C EV Distributed Along Feeder

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## C.1 0% Background Harmonic Distortion

The results presented in section 4.2 showed the probability of failure for a number of vehicles randomly distributed along an urban or rural feeder based on the alternative calculation for $Z_h$ (equation 2-2).. This section presents results based on equation 2-1 for both rural and urban networks. Results are included to compare the impact of the median and upper quartile EV profile along with the assumed background distortion levels.

### C.1.1 Urban Network – WPD Background

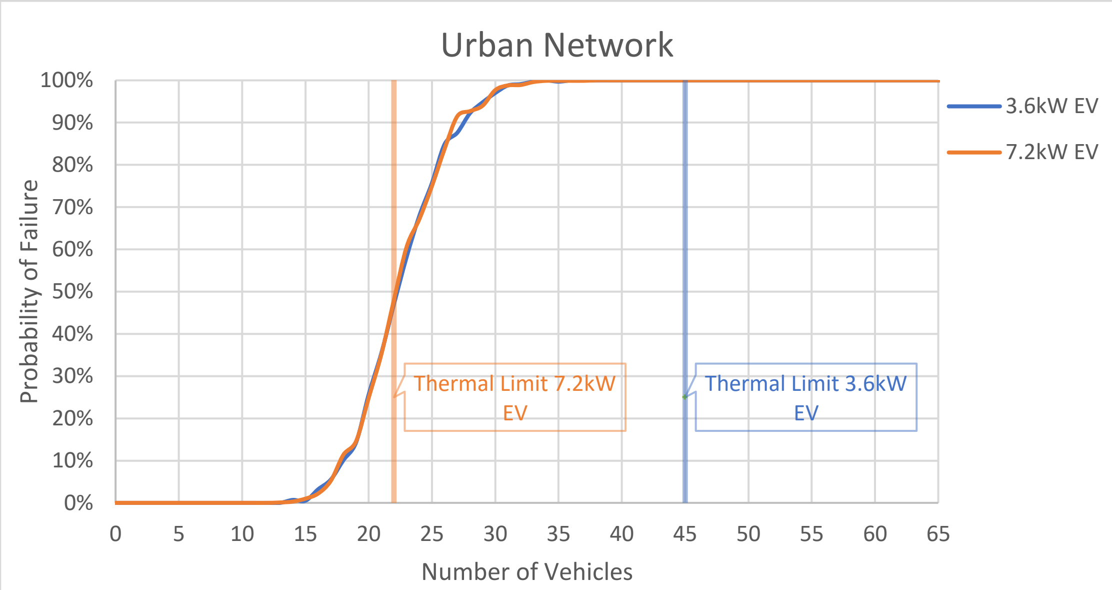


**Figure C-1: Urban network with typical median EV harmonic current, WPD background harmonic distortion and $Z_h$ calculated as per equation 2-1**

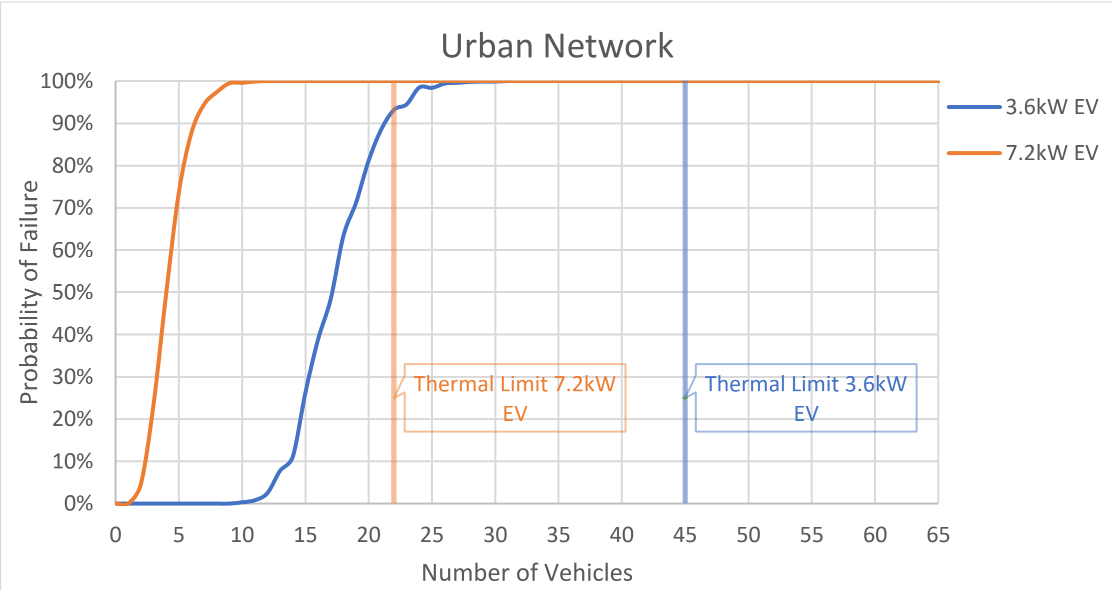


**Figure C-2: Urban network with typical upper quartile EV harmonic current, WPD background harmonic distortion and $Z_h$ calculated as per equation 2-1**

### C.1.2 Urban Network – 0% Background

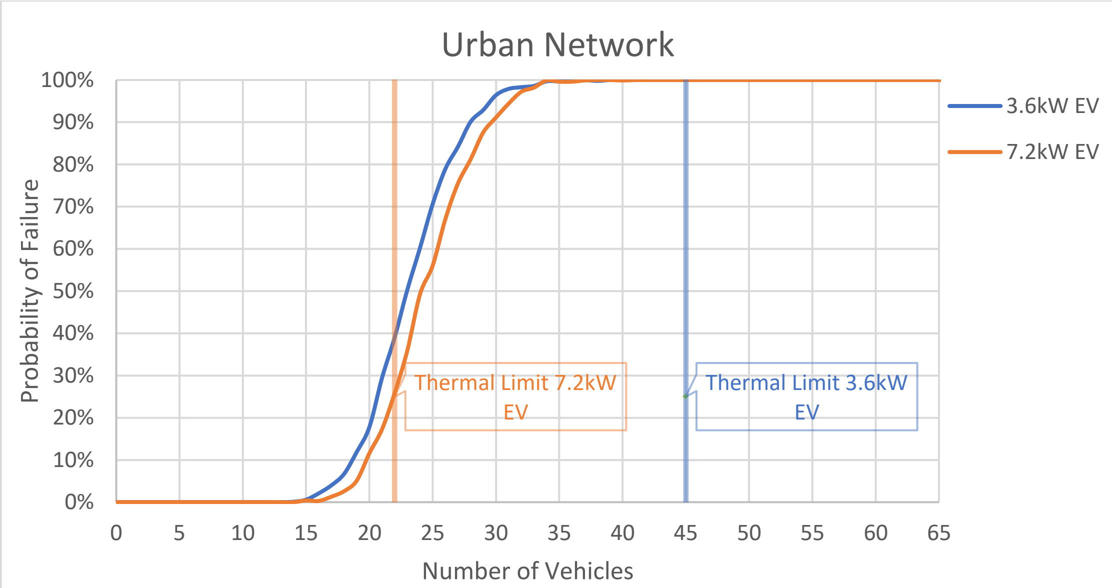


**Figure C-3: Urban network with median EV profile, 0% background harmonic distortion and $Z_h$ as per equation 2-1**

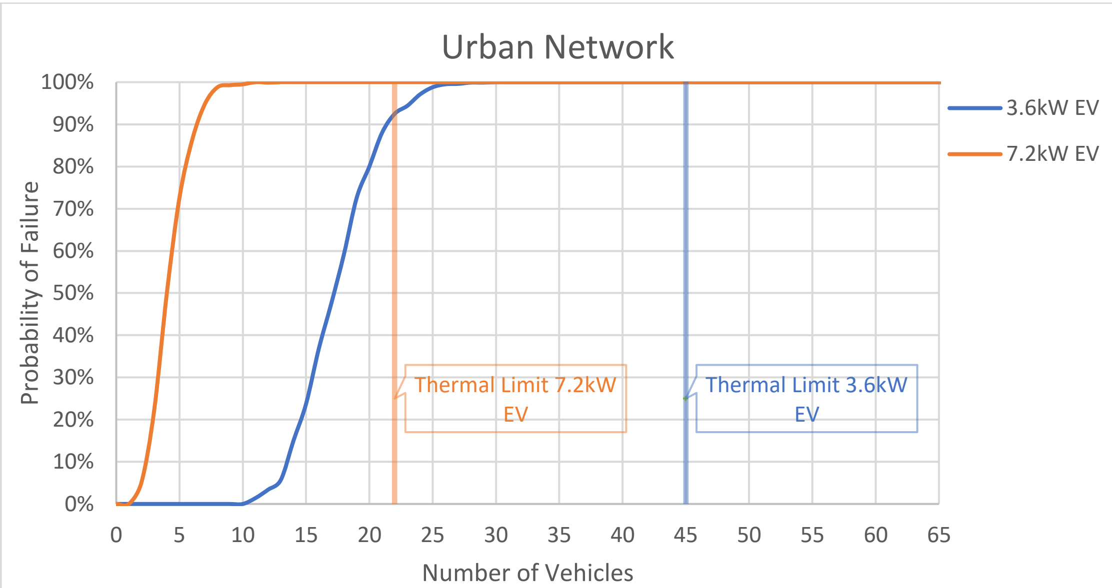


**Figure C-4: Urban network with upper quartile EV profile, 0% background harmonic distortion and $Z_h$ as per equation 2-1**

### C.1.3 Rural Network – WPD Background

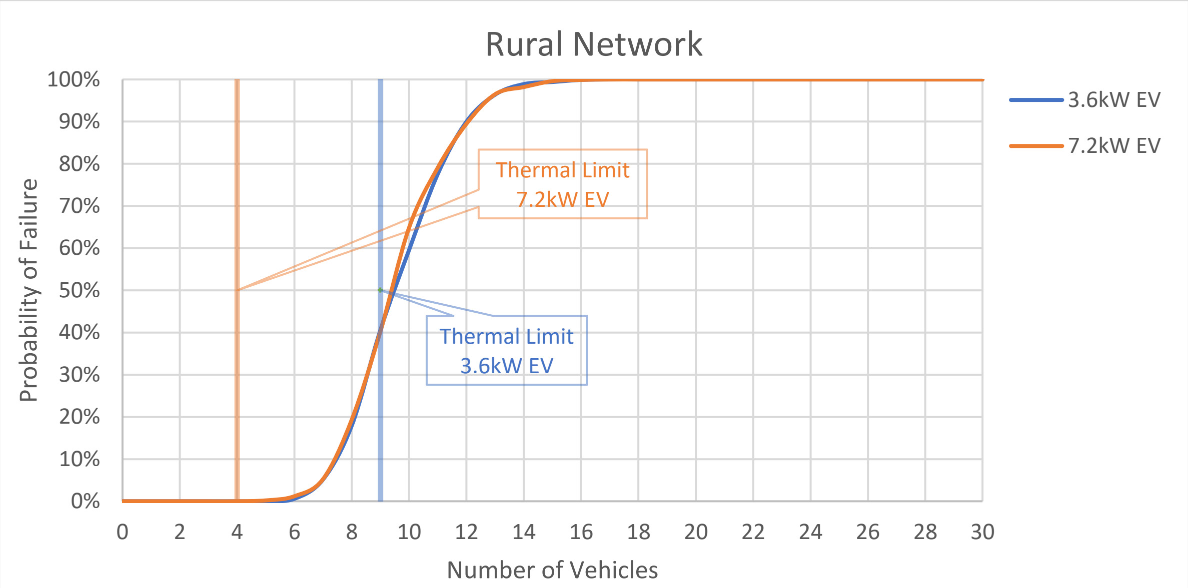


**Figure C-5: Rural network with typical median EV harmonic current, WPD background harmonic distortion and $Z_h$ calculated as per equation 2-1**

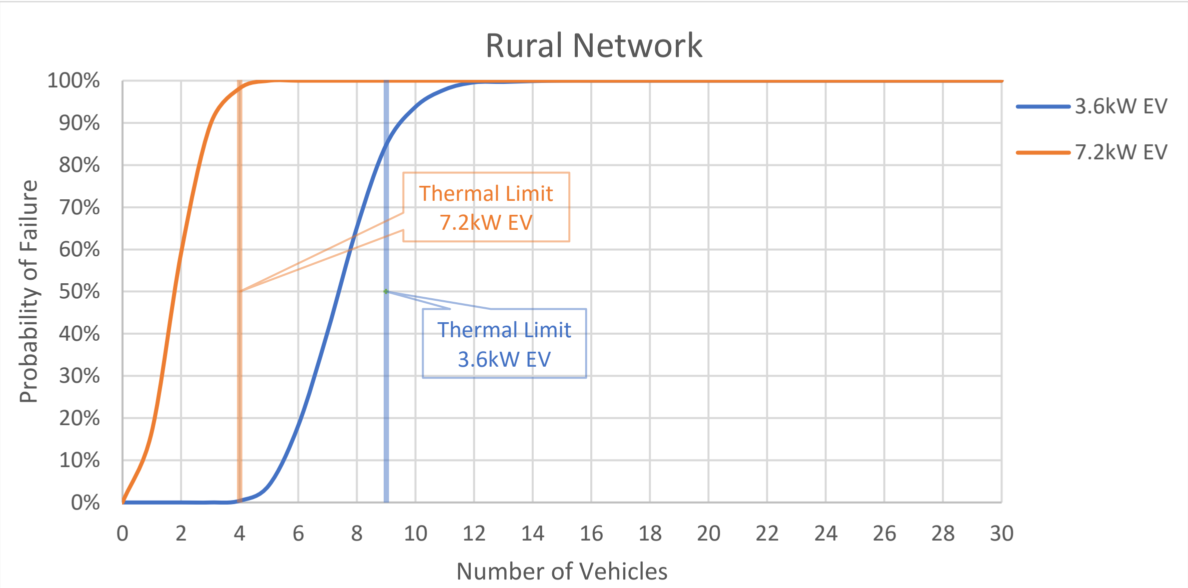


**Figure C-6: Rural network with typical upper quartile EV harmonic current, WPD background harmonic distortion and $Z_h$ calculated as per equation 2-1**

### C.1.4 Rural Network – 0% Background

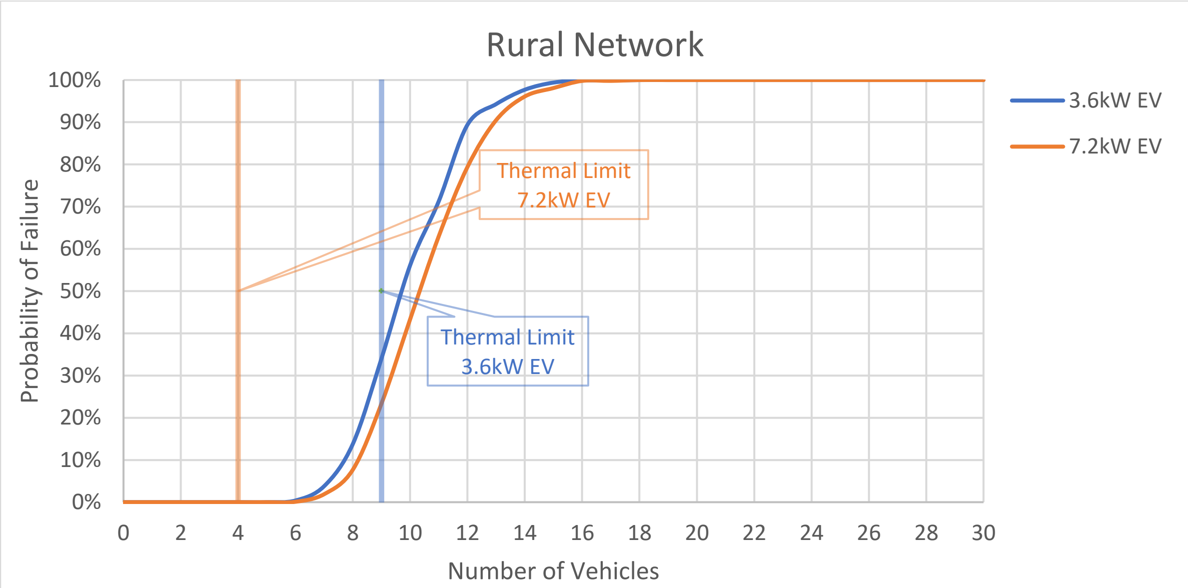


**Figure C-7: Rural network with median EV profile, 0% background harmonic distortion and $Z_h$ as per equation 2-1**

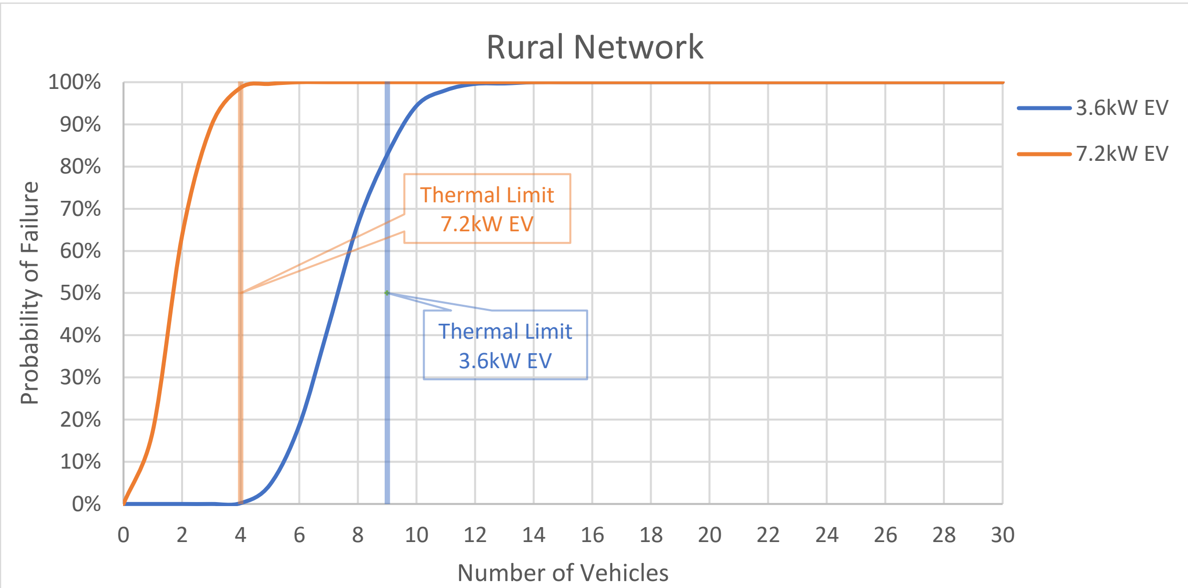


**Figure C-8: Rural network with upper quartile EV profile, 0% background harmonic distortion and $Z_h$ as per equation 2-1**

## C.2 Alternative $Z_h$ Calculation

This section presents results based on the alternative $Z_h$ calculation (equation 2-2) assuming there is no background harmonic distortion.

### C.2.1 Urban Network – 0% Background

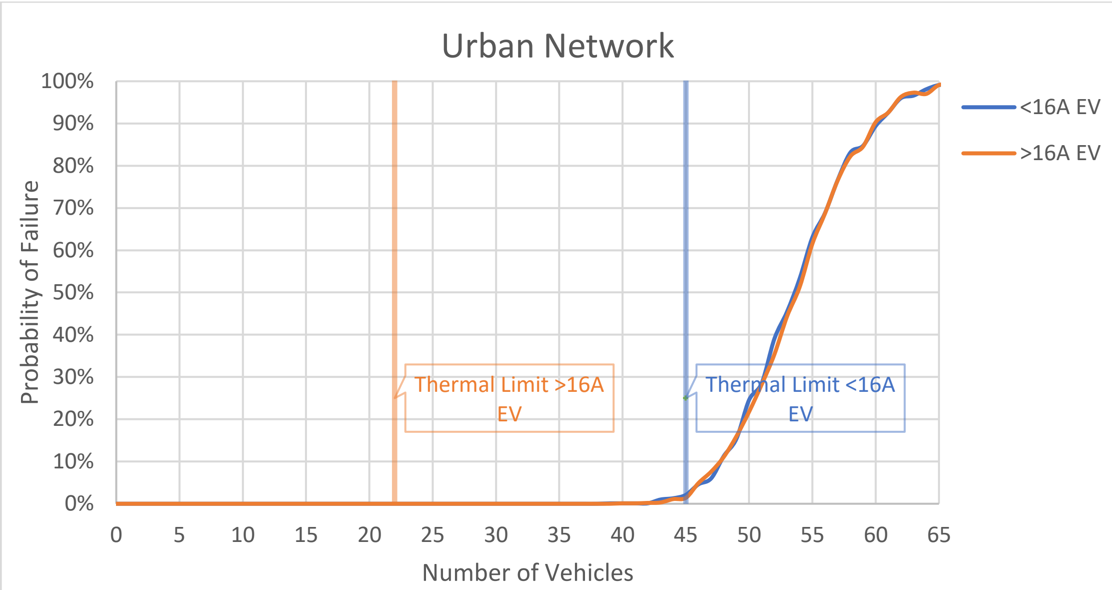


**Figure C-9: Urban network with median EV profile, 0% background harmonic distortion and $Z_h$ as per equation 2-2**

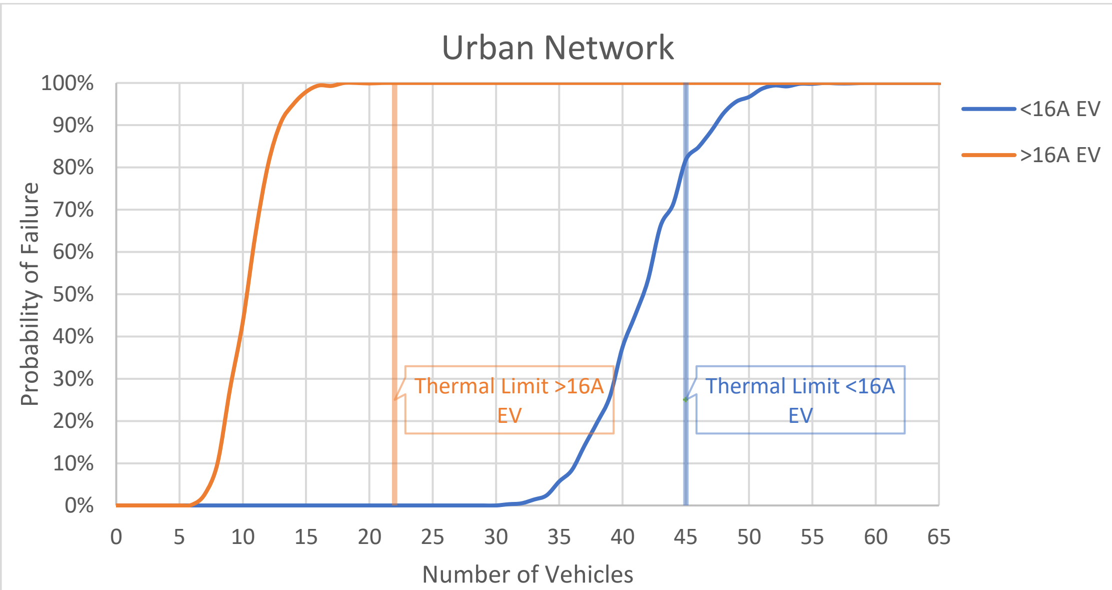


**Figure C-10: Urban network with upper quartile EV profile, 0% background harmonic distortion and $Z_h$ as per equation 2-2**

### C.2.2 Rural Network – 0% Background

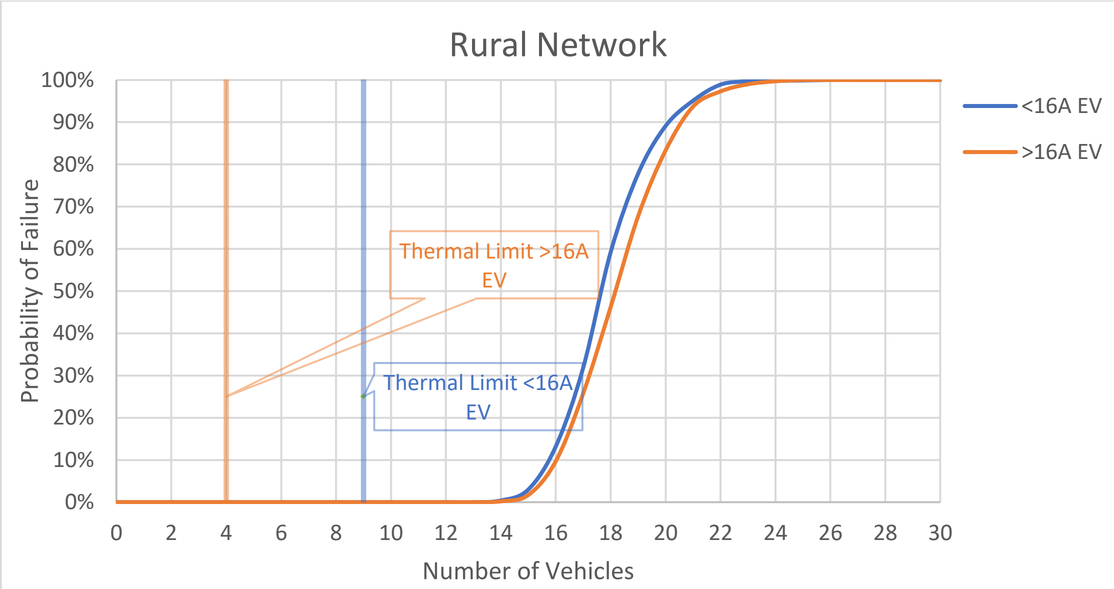


**Figure C-11: Rural network with median EV profile, 0% background harmonic distortion and $Z_h$ as per equation 2-2**

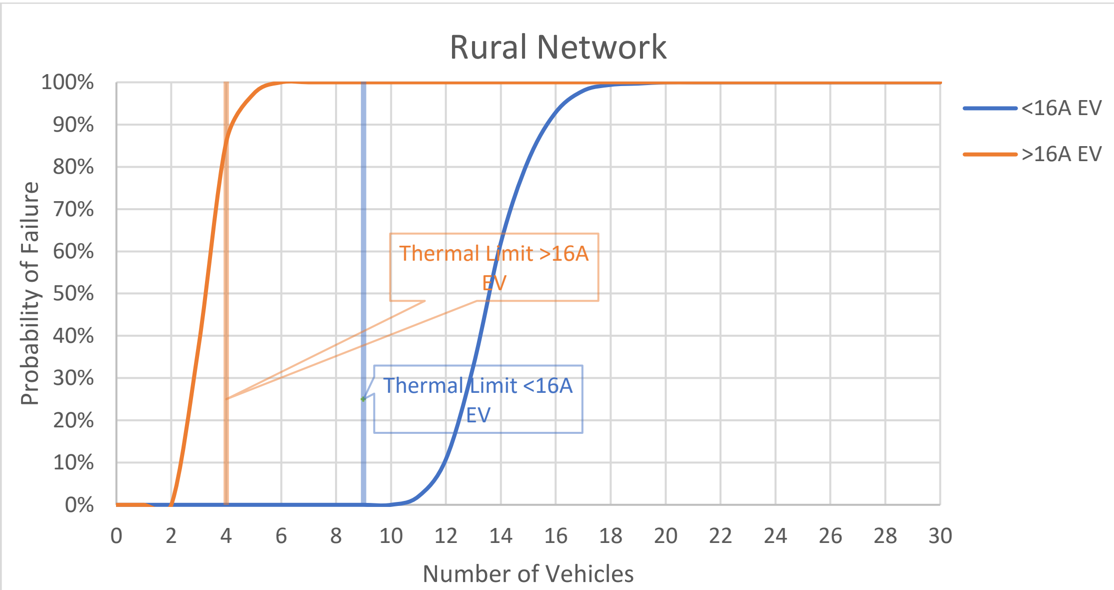


**Figure C-12: Rural network with upper quartile EV profile, 0% background harmonic distortion and $Z_h$ as per equation 2-2**

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