Impact of Electric Vehicle Chargers on a Low Voltage Distribution System

Neville R. Watson [*1], Jeremy D. Watson [*1], Russell M. Watson[2], Kashani Sharma[2], Allan Miller [3]

[1] University of Canterbury, Christchurch, New Zealand
[2] Northpower Ltd, New Zealand
[3] EPECentre, University of Canterbury, Christchurch, New Zealand

Abstract:

The desire to reduce our reliance on fossil fuel and reduce the emission of greenhouse gases has led to an increasing interest in the use of Electric Vehicles (EVs), whether all electric or plug in hybrid electric vehicles (PHEV). New Zealand is ideally suited for the uptake of EVs since most of the electricity generation is from renewable resources. The main barriers from a customer perspective to the uptake of electric vehicles are; price, lack of charging infrastructure and range anxiety. From an electrical utility perspective there are questions regarding the potential impact to the network of wide spread adoption of EVs. To identify these potential issues simulation studies are required. To enable simulation studies to be performed accurate data is required. This paper presents the measurement results obtained for different charger technologies and different cars. These were obtained at New Zealand's first public EV charging station in Whangarei. This data, along with realistic low voltage (LV) distribution feeder data, is then used to perform studies on different LV networks to identify the penetration level of EV chargers that a typical system can withstand without adverse effects.

Presenters: Neville Watson and Jeremy Watson

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Abstract

The desire to reduce our reliance on fossil fuel and reduce the emission of greenhouse gases has led to an increasing interest in the use of Electric Vehicles (EVs), whether all electric or plug in hybrid electric vehicles (PHEV). New Zealand is ideally suited for the uptake of EVs since most of the electricity generation is from renewable resources. The main barriers from a customer perspective to the uptake of electric vehicles are; price, lack of charging infrastructure and range anxiety. From an electrical utility perspective there are questions regarding the potential impact to the network of wide spread adoption of EVs. To identify these potential issues simulation studies are required. To enable simulation studies to be performed accurate data is required. This paper presents the measurement results obtained for different charger technologies and different cars. These were obtained at New Zealand's first public EV charging station in Whangarei. This data, along with realistic low voltage (LV) distribution feeder data, is then used to perform studies on different LV networks to identify the penetration level of EV chargers that a typical system can withstand without adverse effects.

1. Introduction

The potential benefits of adopting electric vehicles (EVs) are immense, provided they can be introduced in a way that does not adversely affect the electrical distribution system [1][2]. This paper builds on the previous LV modelling work by using the same LV system and clustering as reported previously [3]. The procedure to determine the impact of EV chargers on the low voltage (LV) distribution system is similar to that used for PV impact studies. An overview of the approach is shown in Figure 1.

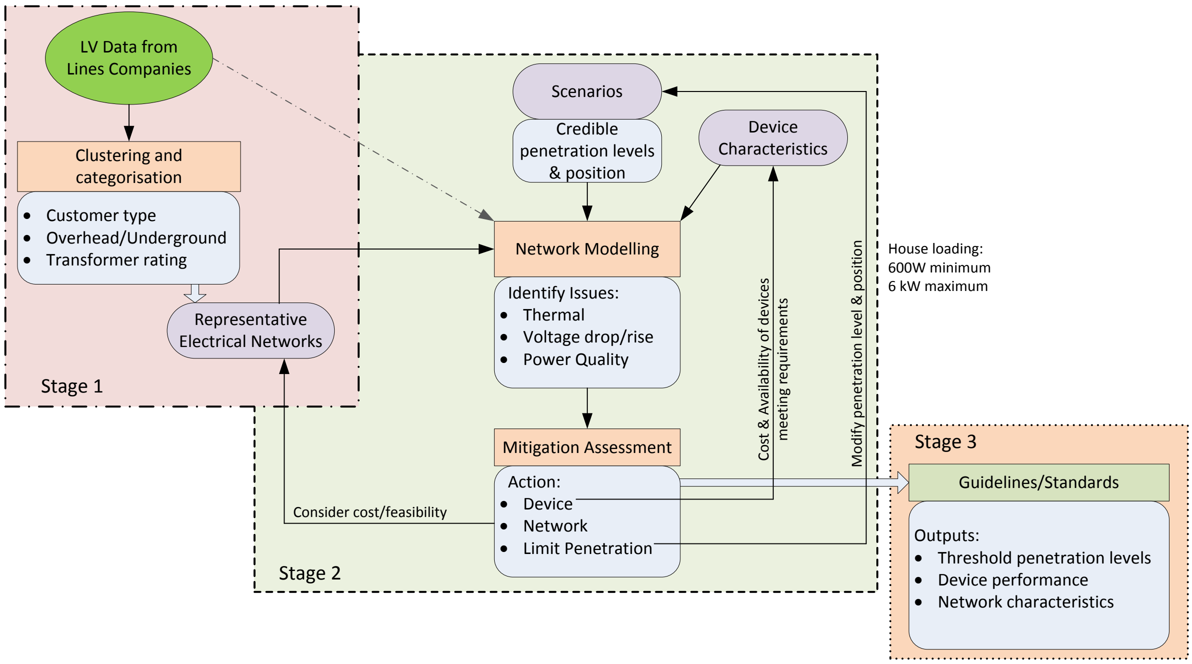

Figure 1. Master plan of LV modelling for power quality

2. Overview of EV Chargers

Many electric vehicles (such as the Nissan Leaf and Mitsubishi MiEV) have two sockets for charging, one AC and one DC for fast charging. However, some cars, such as the Ford Focus Electric, do not provide sockets for fast charging at all. For the Nissan Leaf both are at the front (Figure 2), while for the Mitsubishi MiEV they are on different sides of the car near the rear. The AC socket uses the five pin J1772 connection (Figure 3), which is an industrial standard. The J1772 is more than just a plug but also the communication protocol between the charging station and EV. When connected to this AC socket it is the EV's onboard charger that charges the batteries, the charging station communicates with the car to initiate charging and determines the rate at which the batteries are charged. The performance of the onboard charger was tested using two methods of charging. The in-line (or in-cable) charger that comes with every EV (Figure 4), and a faster wall-mounted ac charger (Figure 5) supplied by JuicePoint, which will be referred to as Wall Charger. The J1772 signalling protocol has been designed to enable:

1. Supply equipment signals presence of AC input power
2. vehicle detects plug via proximity circuit (thus the vehicle can prevent driving away while connected)
3. control pilot functions begin
    - supply equipment detects plug-in electric vehicle
    - supply equipment indicates to EV readiness to supply energy
    - EV ventilation requirements are determined
    - supply equipment current capacity provided to EV
4. EV commands energy flow (pins not energized until EV plugged in).
5. EV and supply equipment continuously monitor continuity of safety ground
6. charge continues as determined by EV
7. charge may be interrupted by disconnecting the plug from the vehicle

Figure 2: DC (left) and AC (right) sockets.

SAE (Society of Automotive Engineers) J1772-2009 connector specification has been added to the international IEC 62196-2 standard. The IEC 62196 standard covers electrical connectors, cables and charging modes for electric vehicles, and defines four charging modes:

Mode 1- slow charging from a household socket

Mode 2 - slow charging from a household socket with in-cable protective device

Mode 3 - slow of fast charge using EV socket with control and protection function installed

Mode 4 - fast charge using an external charger (e.g. CHAdeMO)

IEC 62196 covers conductive charging systems (as opposed to Inductive Power Transfer technology) with rated operating voltage not exceeding 690V a.c. (50-60 Hz) at a rated current ≤ 250A or 600V d.c. at a rated current ≤ 400A.

The world is split on charging connector and communication protocol and the IEC 62196 has been written to encompass the various systems. Japan & North America mainly use the Type 1 connector (J1776) while Europe and China have adopted Type 2 (VDE-AR-2623-2-2, or CEEplus connectors) which contains extra control wires.

The faster JuicePoint ac charger is a single-phase device and can be configured to what the ac system can withstand (IEC62196 Mode 3). Typically 16A or 32A, in this case16 Amps.

In 2011 it was announced that a combined AC & DC connector would be developed by adding DC connections to the existing AC connector types to avoid requiring two charging sockets. This is now known as the CCS (combo charging system), SAE Combo, or SAE Combo DC Faster Charge system. It uses the HomePlug GreenPHY communication protocol. However, the additional cost of developing a dual-protocol rapid dc charger is modest and will be the direction that will be taken.

Figure 3: J1776 plug

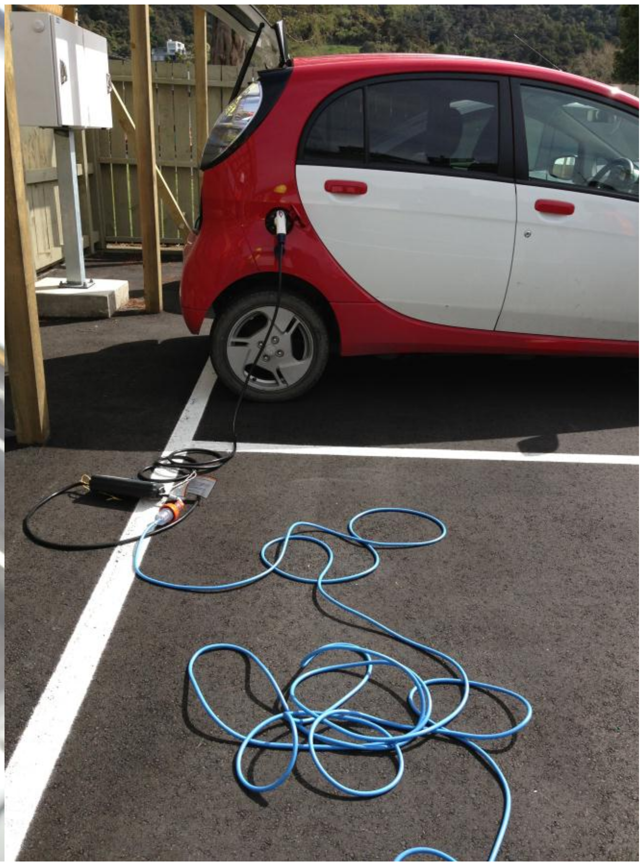

Figure 4: In-Line AC Charger

Figure 5. Faster AC Charger (supplied by JuicePoint)

The DC socket gives direct connection to the DC busbar of the batteries and is used by rapid DC chargers. CHAdeMO is a trade name for a rapid charger initially pioneered by the Tokyo Electric Power Company (TEPCO). Nissan, Mitsubishi, Fuji Heavy Industries (Subaru) and Toyota have also joined the CHAdeMO Association. The CHAdeMO charger takes a 3-phase ac supply and converts it to dc and is capable of delivering up to 62.5 kW (shown in Figure 6). The TEPCO DC connector also makes data connection using the CAN bus protocol. Functions such as safety interlock (to stop energisation before connected to the car), transmitting battery parameters (such as target voltage and total battery capacity). Some are predicting the obsolesces of CHAdeMO, particularly in Europe, as the European Parliament wants to stop installing CHAdeMO charging station by 2019 [4,5] in favour of the SAE CCS (Combined Charging System) combo. Both SAE CCS combo plug or the Tesla connector are contenders for the future, with the CCS backed by the American and German car manufacturers. The desire to allow vehicle to grid transfer has resulted in some looking to Smart Grid protocols (PLC or HomePlug GreenPHY communication protocol) to ease the implementation of the EV being used as a battery on wheels to support the grid. CHAdeMO now allows bi-directional transfer to support Vehicle to Grid (V2G) or Vehicle to Home (V2H) system. CHAdeMO have announced that two car manufacturers now have Vehicle to Home (V2H) systems using CHAdeMO protocol and connector. The impetus for Nissan to develop the V2H system was the 2011 earthquake and tsunami [6]. This involves the installation of a Power Control System to the house's electrical distribution board and connecting this to the car's DC quick charge socket.

Not all EVs cater for CHAdeMO and some newer European EVs (Renault Twizy and Kangoo, Tesla Model S, Ford Focus Electric, Volkswagen E-Up and the BMW i3) are not designed to be compatible with a CHAdeMO charger [4]. However, adaptors have been developed and marketed to allow EVs, such as the Tesla-S (Figure 7), make use of the CHAdeMO rapid chargers.

The CHAdeMO system has proven to be very safe with the plug having a locking mechanism that prevents mishandling by drivers. The CHAdeMO standard has been tested and refined over the years [4]. The website http://www.plugshare.com/ shows the location, type, and availability, of EV chargers worldwide. The CHAdeMO Association’s website (http://www.chademo.com/) shows the locations of CHAdeMO rapid charging stations.

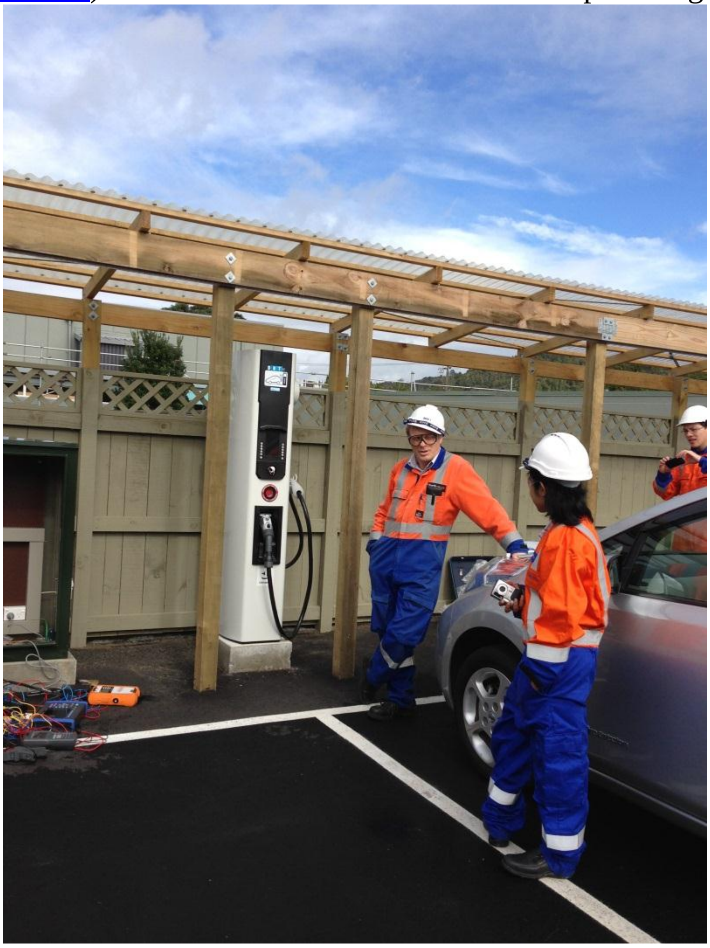

Figure 6. Faster DC Charger (CHAdeMO)

Figure 7. CHAdeMO adaptor for Tesla-S
[http://shop.teslamotors.com/products/chademo-adapter]

2. Technical Performance of EV Chargers

When using the AC Socket the onboard charger is being used to charge the batteries. The in-line (Figure 3) and wall-mounted JuicePoint (Figure 4) charging systems provides the electrical connection and uses the J1772 signalling protocol to communicate to the car what the onboard charger can draw through the connection. The in-line system was set to 10 Amps and the wall-mounted JuicePoint charger to 16Amps. A review of on-board charger topologies is given in [7][8][9].

2.1 Onboard Charger with In-Line charging system

Figure 8 shows the recorded current for the Nissan Leaf, MiEV and Mitsubishi Outlander. Excluding the ramp up transient the Nissan Leaf's Onboard charger draws a steady 10Amps from the AC supply (see Figure 8). The MiEV and Outlander also draw a steady current while charging, but at a slightly lower level. The startup transient is different for the three vehicles. The behaviour of the Onboard charger of the MiEV is similar to the Nissan leaf's, except that the start-up up period for the MiEV is significantly more pronounced (longer) and the current drawn is slightly lower (9.2A). The start-up transient for the Mitsubishi Outlander is smoother and settles to 9.4A.

The corresponding total harmonic distortion (THD) in the current (in %fundamental and Amps) is shown in Figures 9, 10 &11 for the Nissan Leaf, MiEV and Outlander, respectively. The Current THD is very low for the Outlander. Inspection of the individual harmonic (Figures 12, 13 & 14) clearly shows this is due to a dramatic reduction in the 3rd harmonic, which is only slightly larger than the 5th in this case. It can be observed that the Leaf has the highest current distortion, but it is still a lot lower than many other appliances.

Figures 12, 13 & 14 which display the individual harmonics for the Leaf, MiEV and Outlander, respectively. The 3rd harmonic is by far the largest harmonic for the Leaf and MiEV, while it is only slightly larger than the 5th harmonic for the Outlander. The other obvious difference is the variation in the harmonic current levels for the Outlander, whereas the harmonic currents are steady while charging for the Nissan Leaf and MiEV.

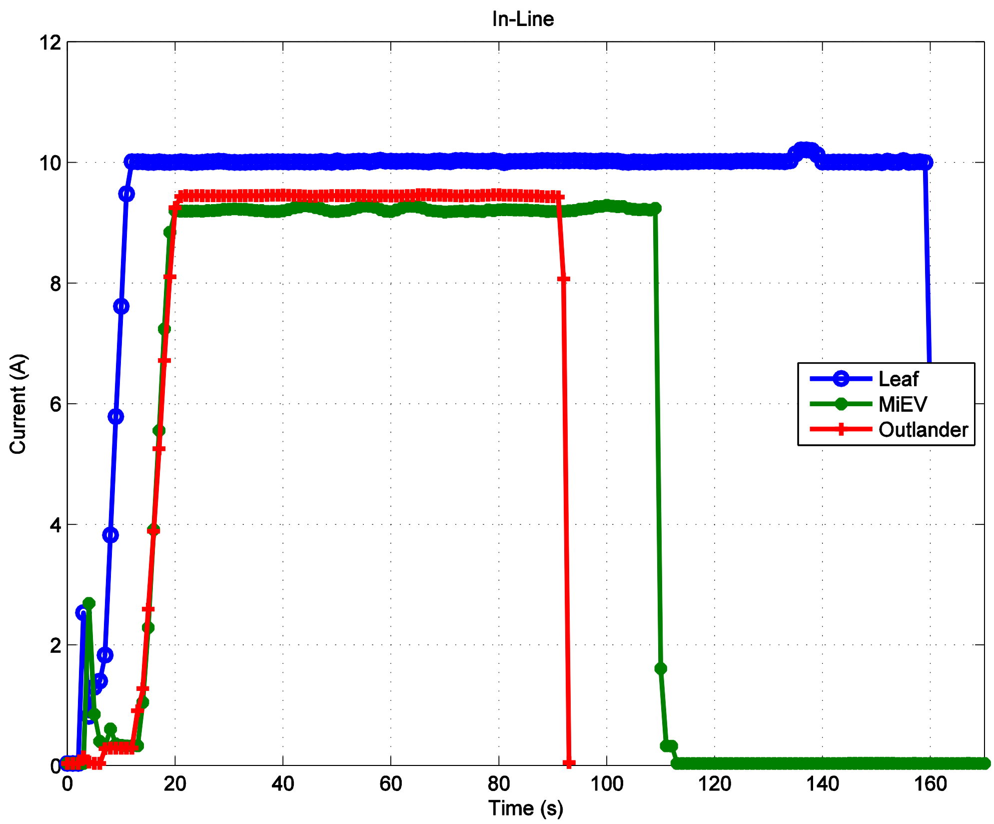

Figure 8. In-Line Charging currents

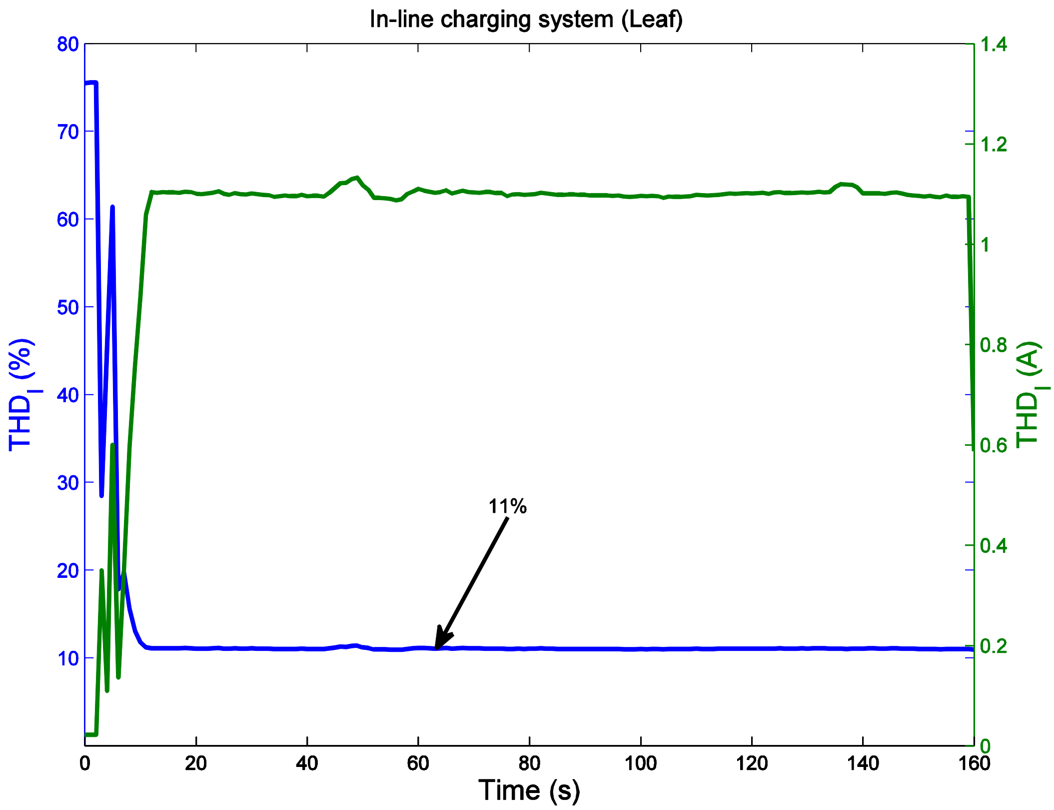

Figure 9. Nissan Leaf

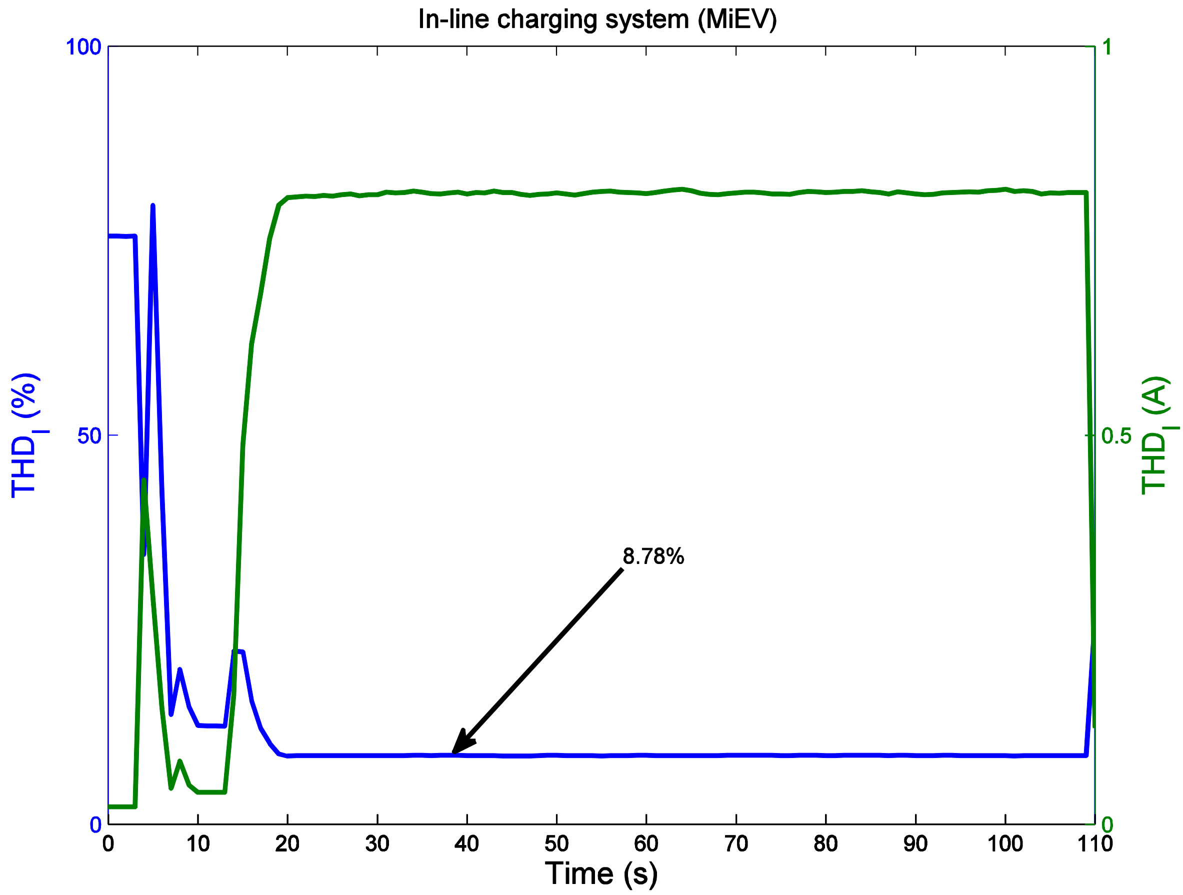

Figure 10. MiEV

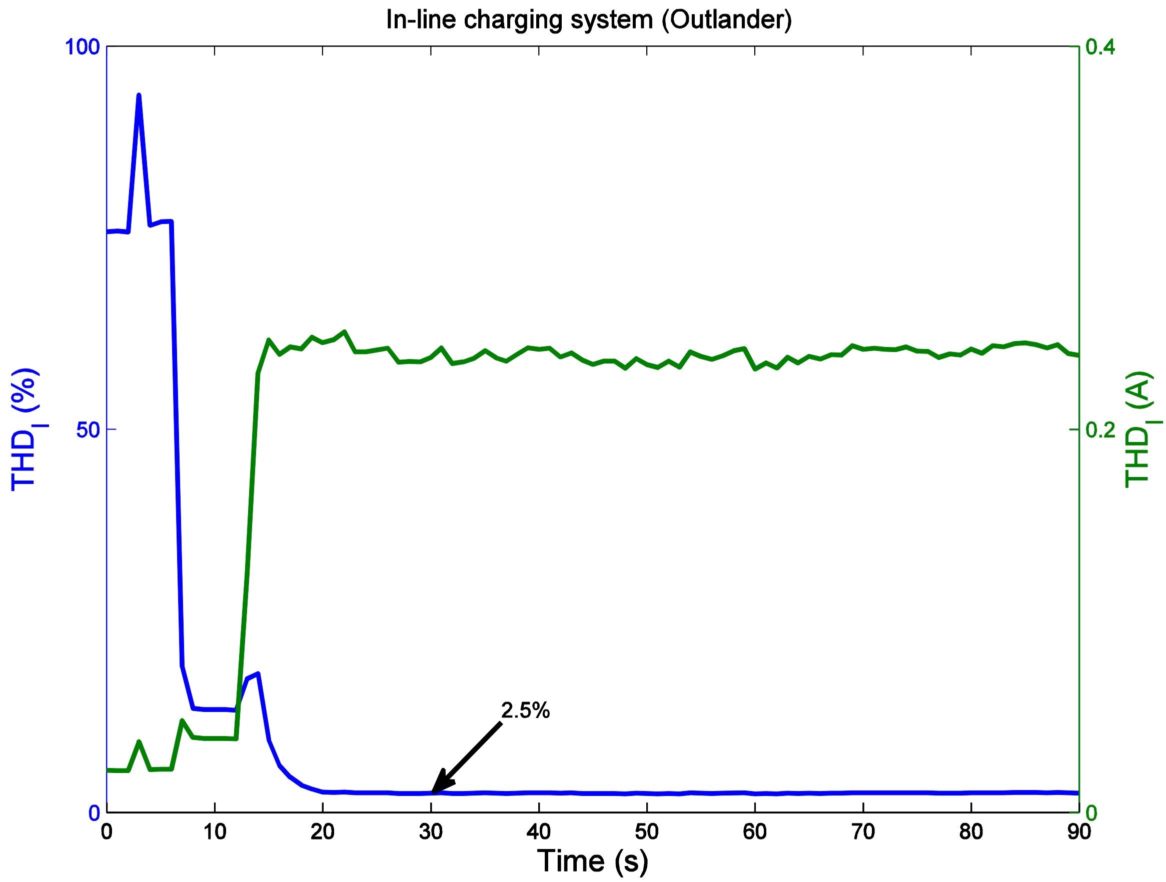

Figure 11. Outlander

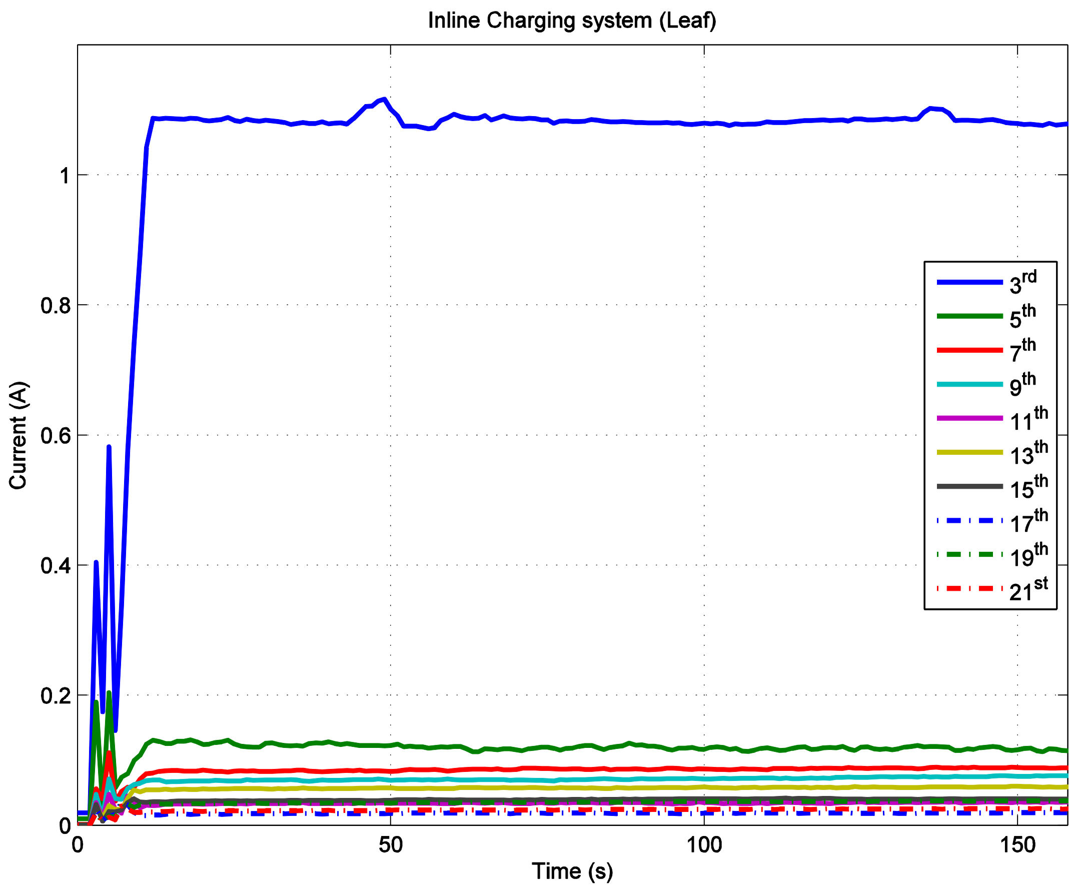

Figure 12. Nissan Leaf

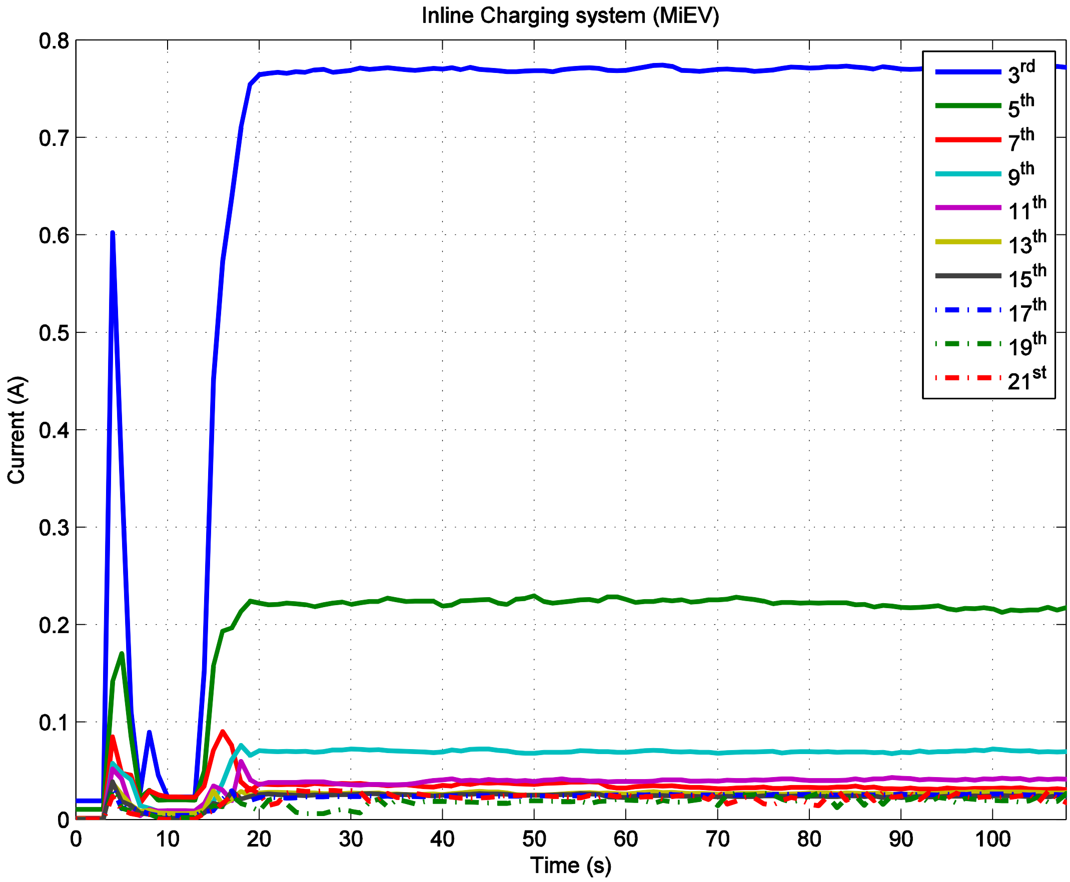

Figure 13. MiEV

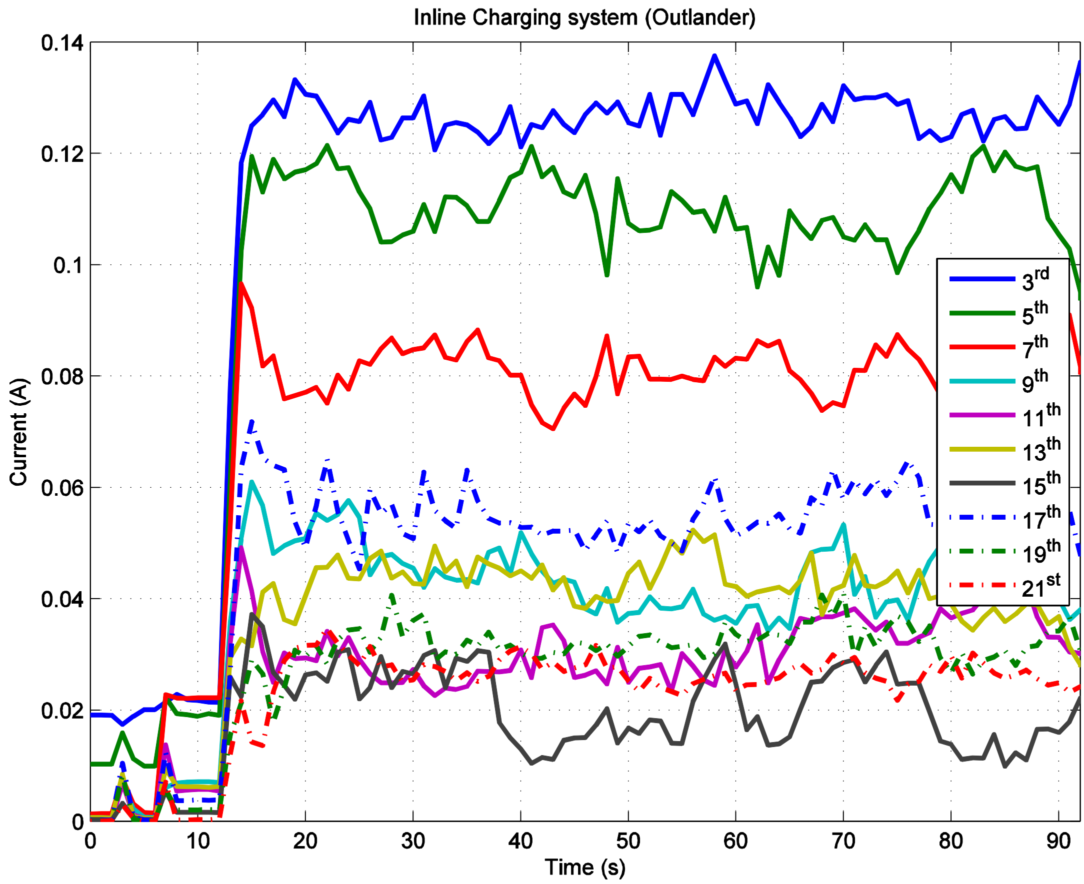

Figure 14. Outlander

2.2 Onboard Charger with JuicePoint's Wall mounted system

The patterns for the Onboard chargers using the JuicePoint wall mounted system mirror the observed behaviour using the Inline, except the steady-state current was higher (16.2A Nissan Leaf, 13.5A MiEV, 14.3A Outlander). The other difference was in the spectrum of the Outlander, where the 5th harmonic exceeded the level of the 3rd harmonic. The trends observed using the in-line charging system are repeated for the Wall mounted charging system, albeit at a higher current level.

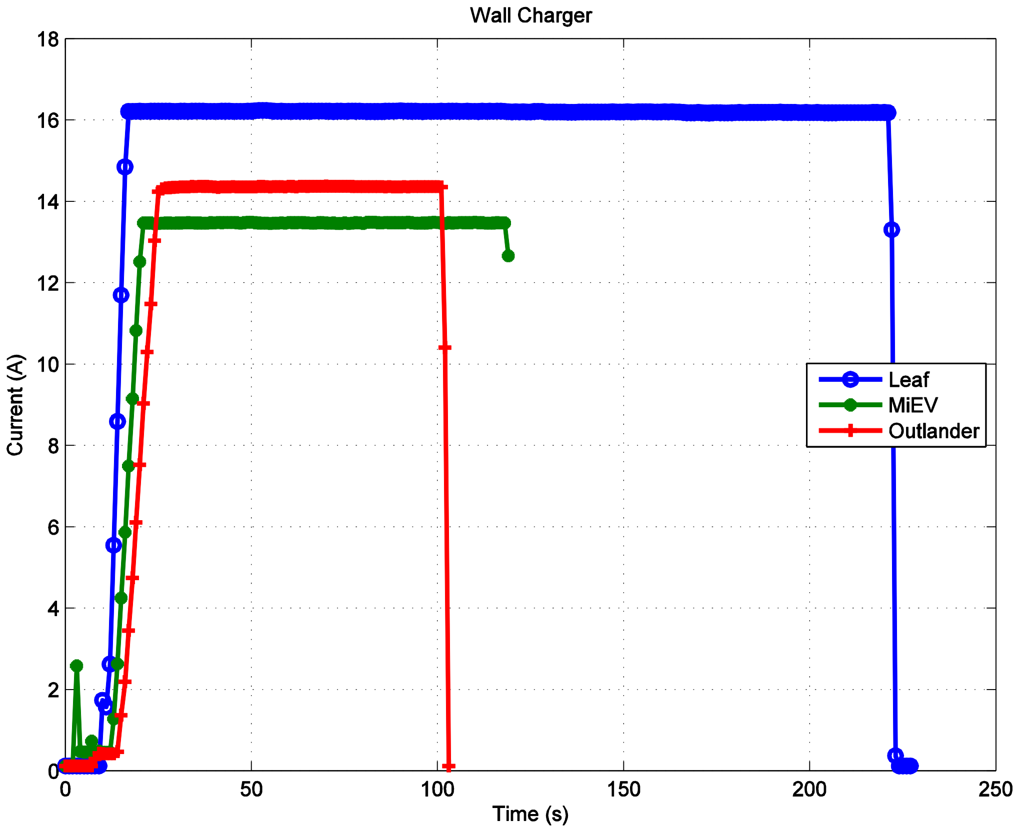

Figure 15. Wall Charger

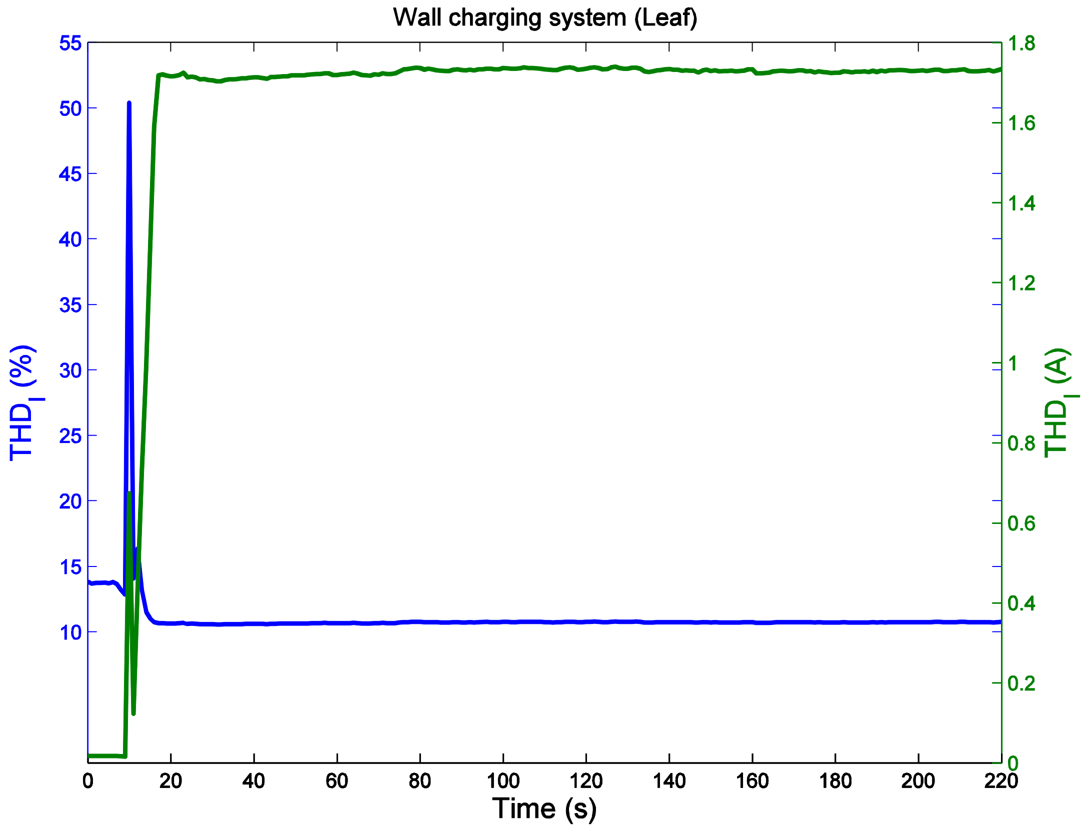

Figure 16. Nissan Leaf

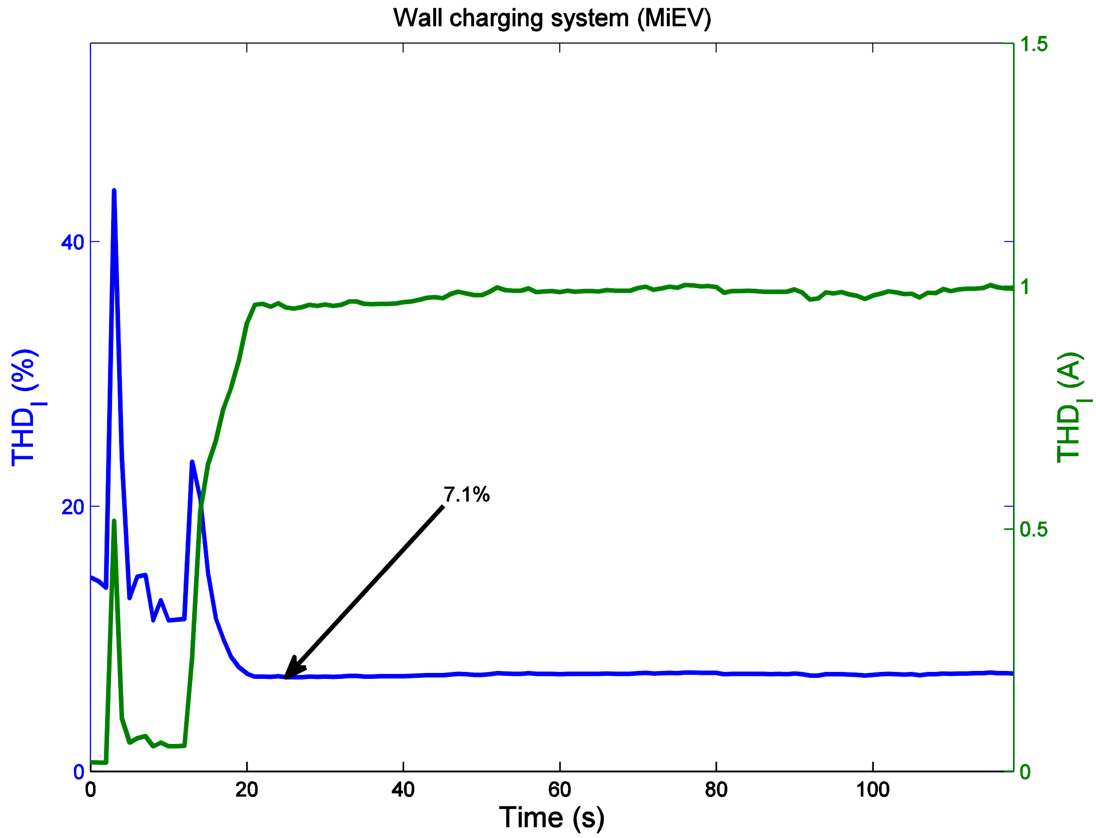

Figure 18. MiEV

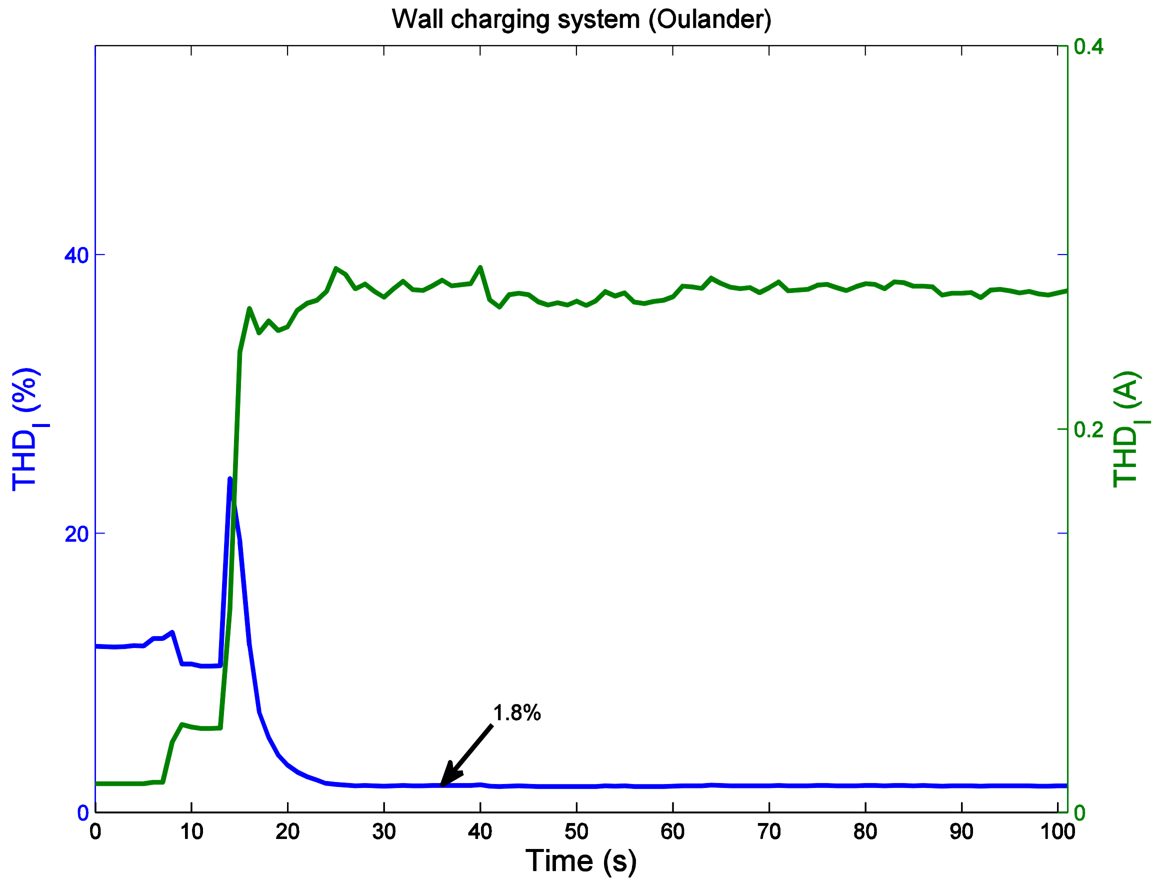

Figure 20. Outlander

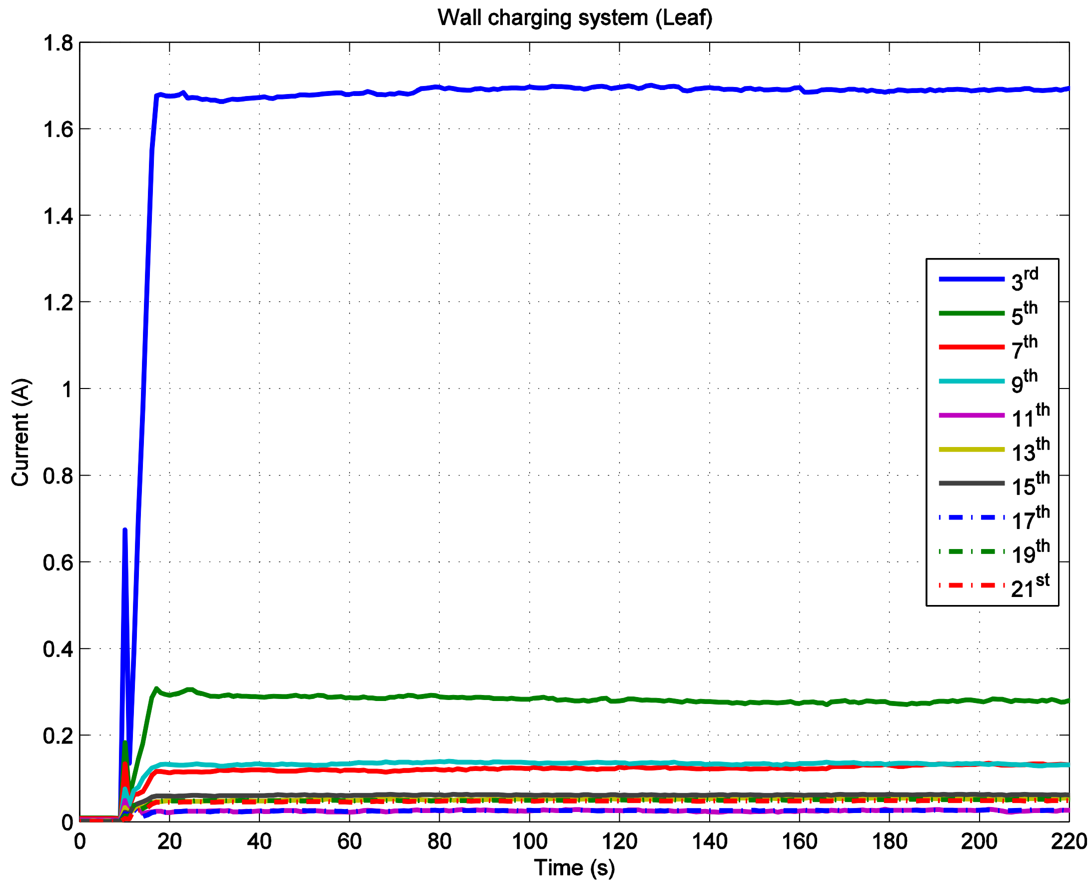

Figure 17. Nissan Leaf

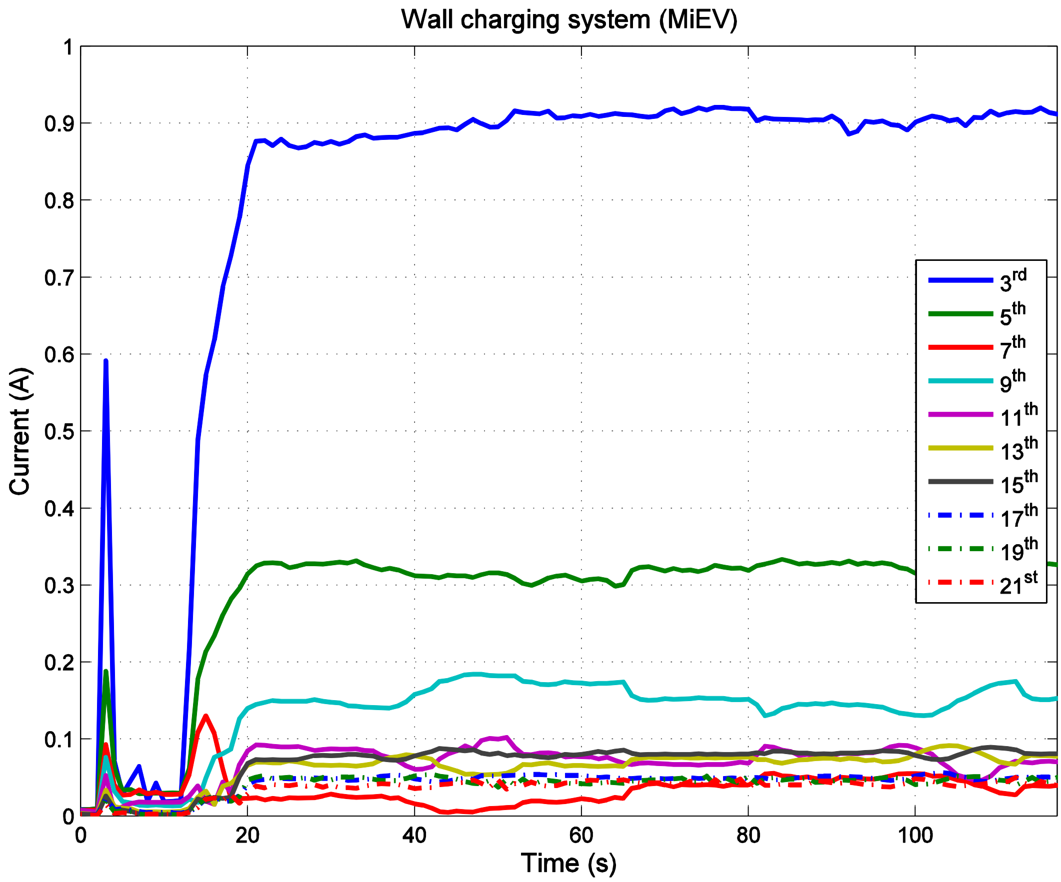

Figure 19. MiEV

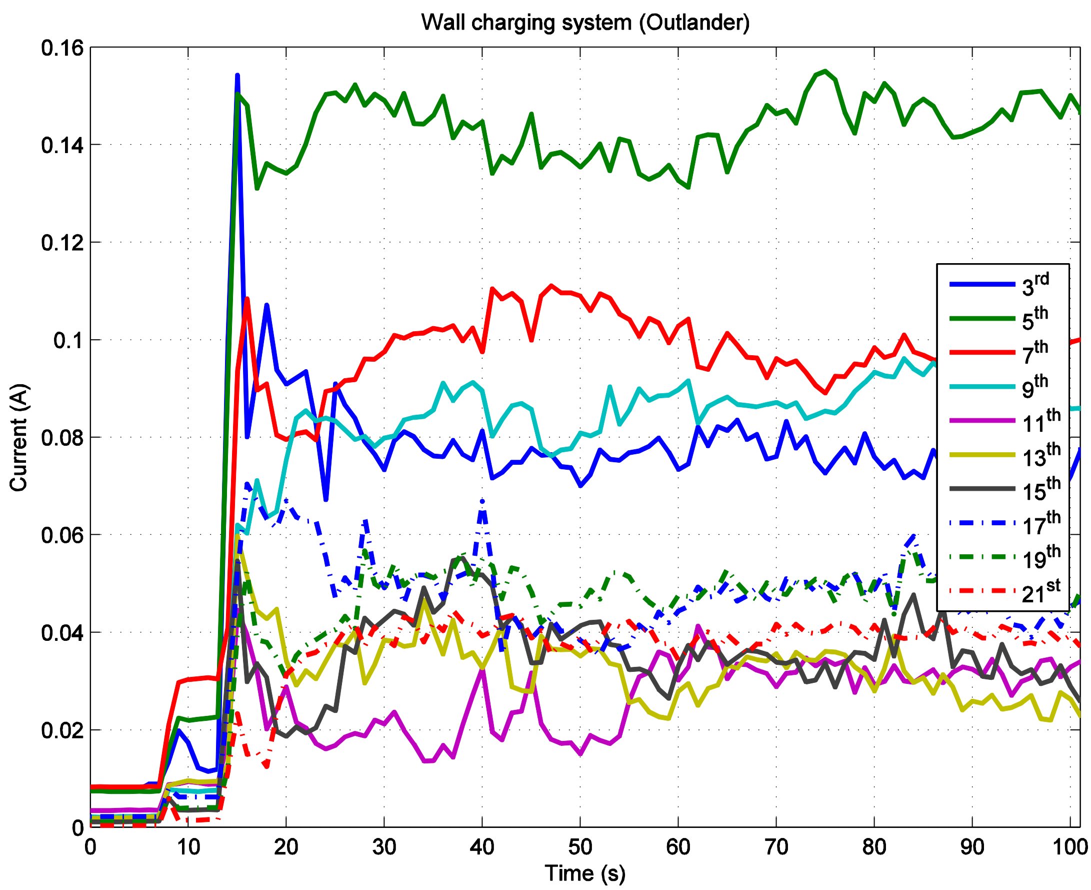

Figure 21. Outlander

2.4 Tesla-S Charging with Type-2 connection

The harmonics from a 22 kW European (IEC 62196 Type 2) charge point, charging a Tesla-S were also measured for two different charge rates, 16A & 32A. The recorded current THD were 4.8% (for 16A) and 6.1% (for 32A). There was significant different in the magnitude of harmonics in each phase. This may be due to the unbalance in the three-phase voltages (between 3 to 4.8% during testing). The 5th was generally the largest harmonic (in Amps). The European Commission has decided that the Type 2 connector will become the single, ratified standard for electric car charging across Europe.

2.4 Summary of AC Charging Systems

Table 1 gives a summary of the RMS level and the THD of the current drawn from the ac supply. The harmonic content is small relative to many other nonlinear loads. Moreover, for the Nissan Leaf and MiEV the 3rd harmonic current is dominant, and although this will generate 3rd harmonic voltage distortion on the LV, it is unlikely so present a problem on the MV.

Table 1. Summary of AC Charging Systems

	In-line		JuicePoint	
Car	I_{THD} (%)	I_{RMS} (A)	I_{THD} (%)	I_{RMS} (A)
Nissan Leaf	11.0	10.9	10.6	16.2
MiEV	8.78	9.25	7.1	13.2
Outlander	2.5	9.48	1.8	14.4

2.5 CHAdeMO rapid DC Charger

The measurements were made on the three-phase supply to the CHAdeMO rapid charger. Unlike the Onboard chargers the CHAdeMO charger does not give a constant charge to the batteries. It ramps up to a set level (approximately 65A) and remains at this until the batteries reach a certain charge level and then tapers of the charge. In Figure 22 the charger does not show a plateau for the Leaf, at a set level, as the charge level set for tapering off occurs before the set level is reached. This is due remain charge left in the Leaf before commencing the charge. The default setting is to take the battery charge to 80% (in the interest of persevering battery life). The current THD in % of fundamental and Amps are displayed in Figures 23 & 24.

The odd and even harmonics are shown in Figures 25-28 for both the Leaf and MiEV. The harmonics are low with the 5th & 7th being dominant for both cases (Figures 25 & 28).

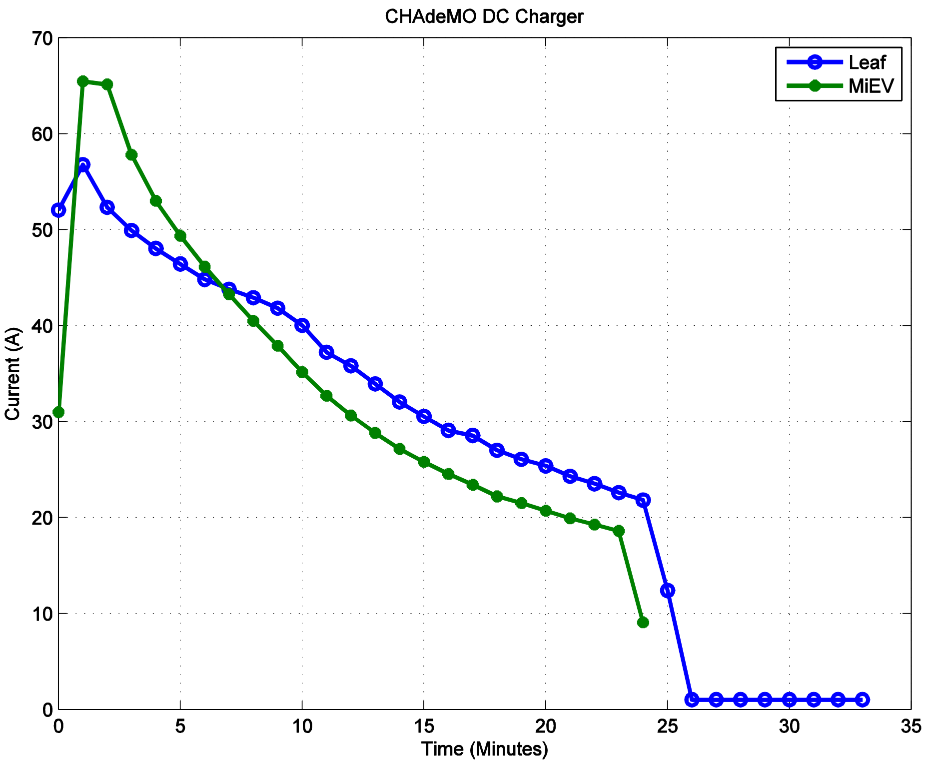

Figure 22. CHAdeMO DC Fast Charger

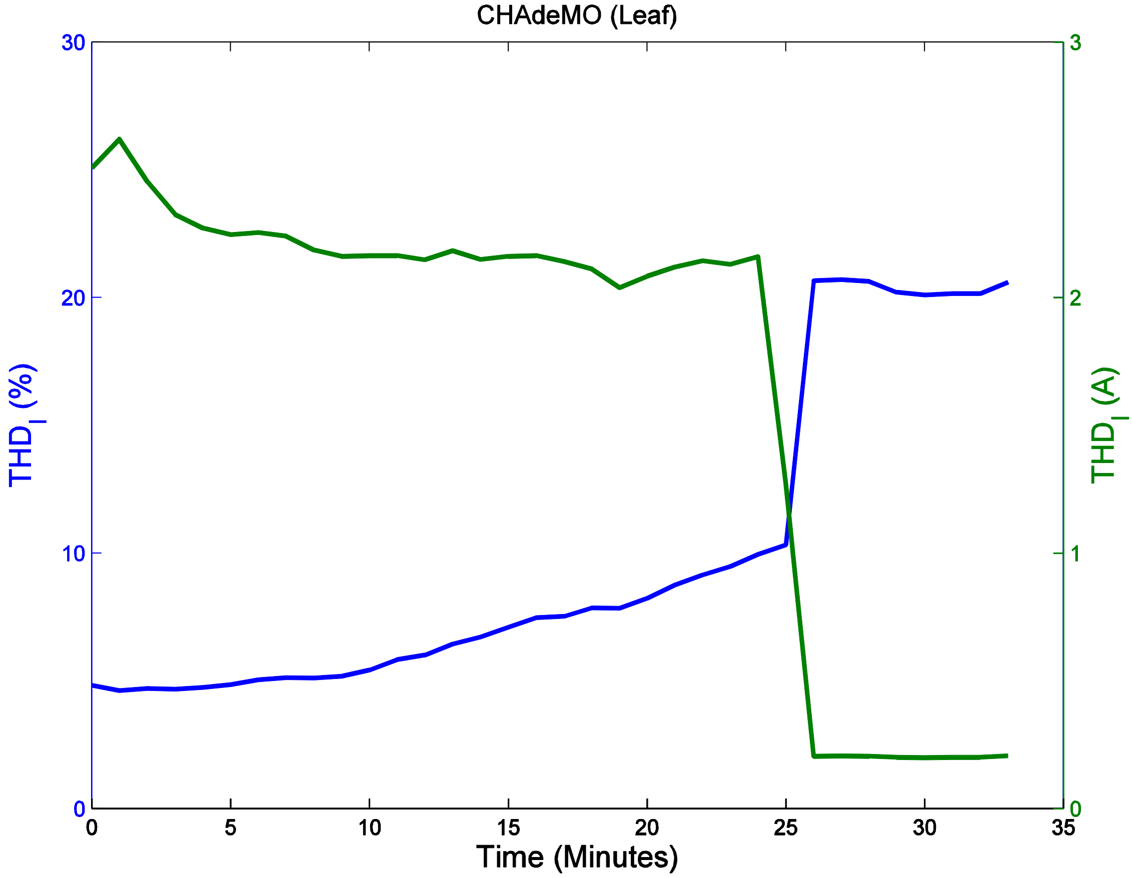

Figure 23. CHAdeMO (Nissan Leaf)

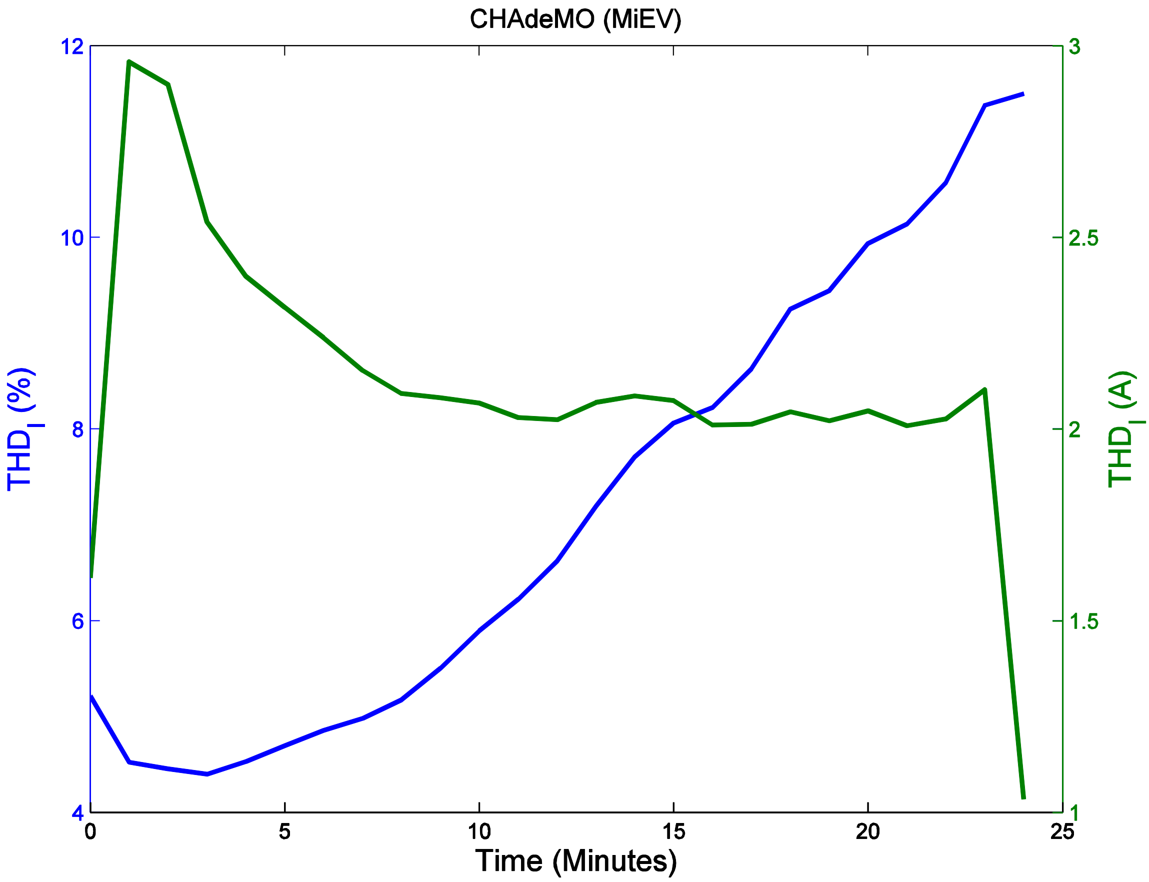

Figure 24.CHAdeMO (MiEV)

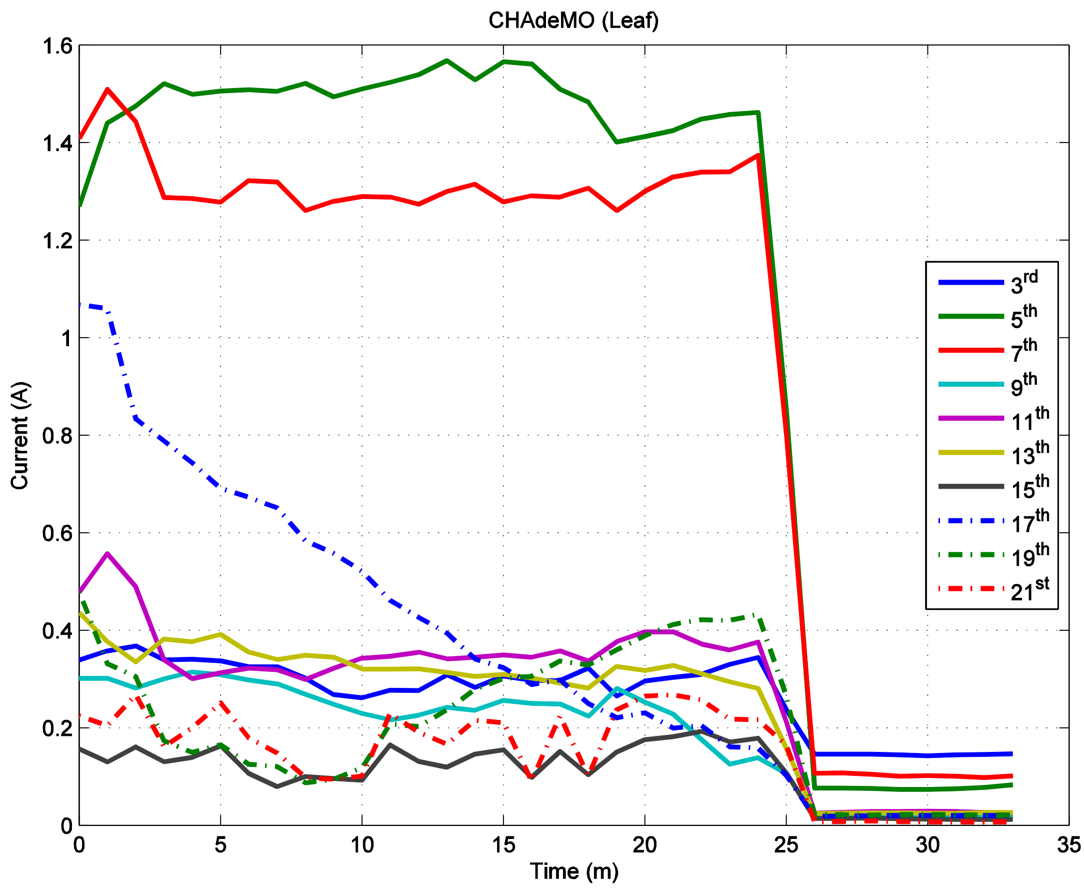

Figure 25. Odd order harmonic currents [CHAdeMO with Nissan Leaf]

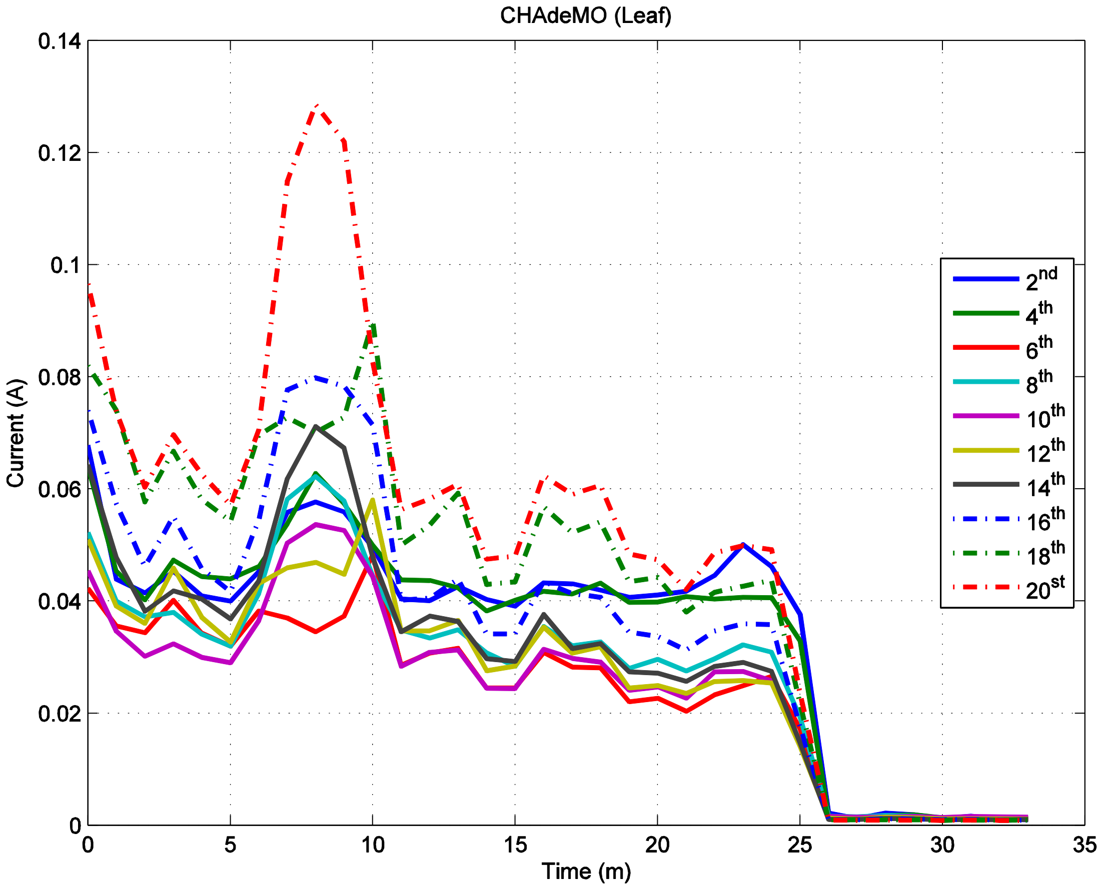

Figure 26. Even order harmonic currents [CHAdeMO with Nissan Leaf]

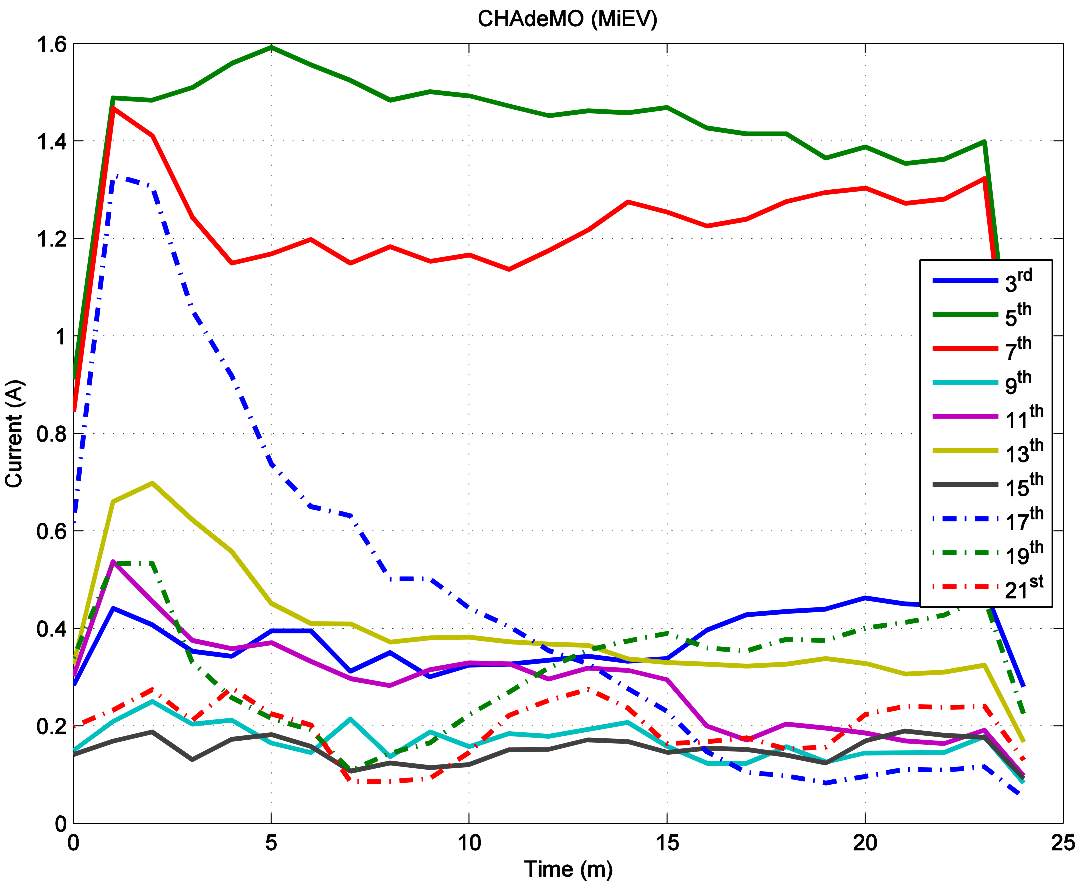

Figure 27. Odd order harmonic currents [CHAdeMO with MiEV]

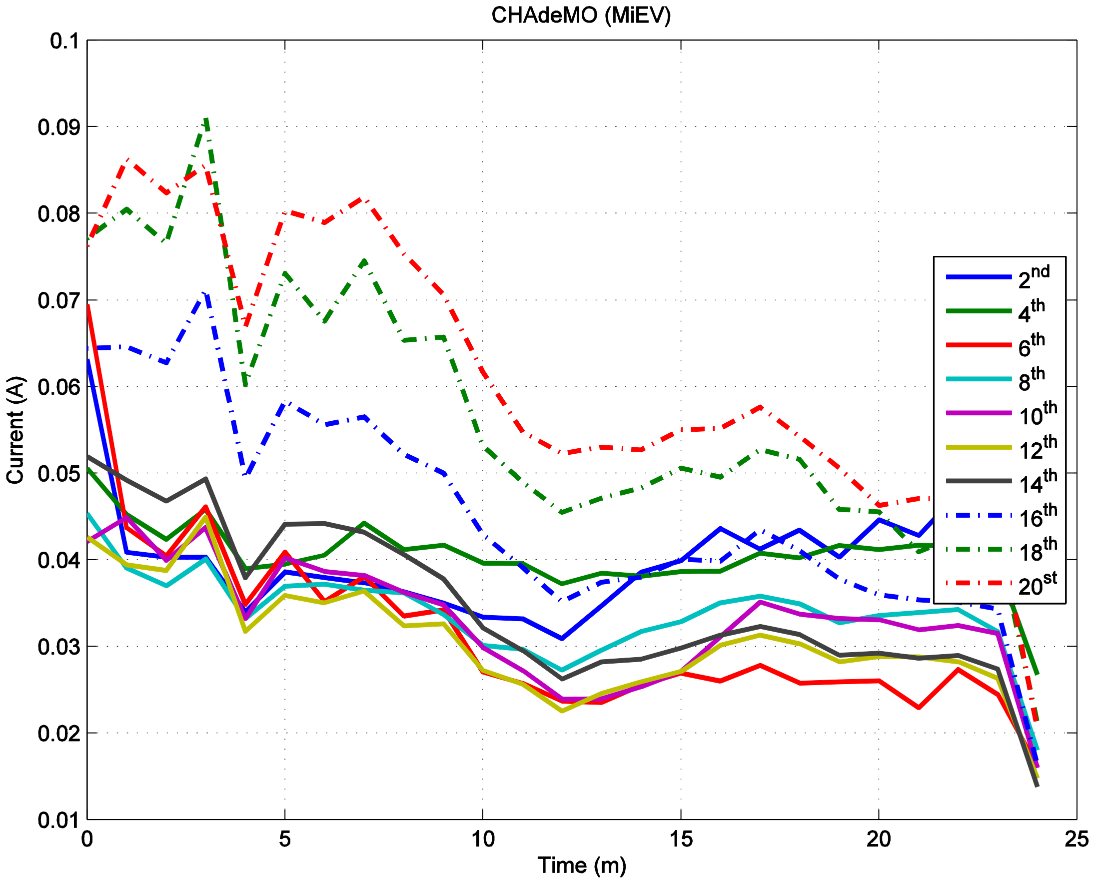

Figure 28. Even order harmonic currents [CHAdeMO with MiEV]

2. Impact on LV network

The excellent study of Orr *et al* compared the performance of five types of battery chargers for use with electric vehicles over one charge cycle [10]. The charger characteristics were determined by simulation of the charger circuit rather than by measurements. This was extended by looking at the combined effect of a cluster of EV on one busbar using a Monte Carlo type of simulation [11]. More recent studies has looked at the impact of EV chargers on distribution transformers, with a view to estimate the effect on transformer life or optimising the charging regime [12][13]. The contribution of Kütt *et al* was to provide a discussion of the possible effects of EV chargers [14]. While it does not contribute any new data or analysis results, it does summarise other researchers' findings.

Lo *et al* modelled 36 EV chargers connected to four 11 kV busbars to calculate the Voltage THD using a direct harmonic penetration program (it was not a harmonic load-flow as claimed by the paper) [15]. Despite the paper's title, the work of Pereyra Zamora *et al* is to develop a methodology for assessment of EV chargers on a Brazilian distribution network [16]. It does not actually give a useful evaluation of the impact of EVs on a distribution system. Another earlier study attempted to investigate the impact that electric chargers in an urban LV distribution network [17]. Due to lack of LV network data at the time an arbitrarily contrived LV network was used. This system is not therefore statistically representative of an urban LV network. Moreover, because a commercial software pack was used (SinCal) each scenario had to be manually created, in particular the loading at each node in the feeder has to be edited, which is a time consuming task. Therefore only a limited number of cases were considered.

Today far more comprehensive LV data is becoming available and has already been used for assessing the impact PV inverters will have on the LV network [3]. Availability of this data has allowed clustering to ensure truly representative networks are identified. Therefore, in order to determine the impact widespread uptake of EVs will have on a New Zealand distribution system the previously reported representative feeders obtained from a New Zealand distribution company have been used. These were; the feeder closest to the centre of a cluster (typical), the feeder on the periphery (worst) and the median (halfway between these two) [3]. This seems to produce a reasonably diverse selection of feeders with varied parameters.

A custom MATLAB power-flow was developed and used for the simulations. MATLAB was primarily chosen because of the flexibility of MATLAB to run many scenarios automatically (without manual intervention), ease of performing statistical analysis and quality of the graphical output of results. The MATLAB power-flow program was first benchmarked against SinCal for one feeder.

2.1 Methodology

Maximum Demand information was available at the supply transformer. Due to lack of more detailed information this was evenly allocated to the ICPs on the feeder. On top of this maximum loading the EV charger loading was added. In some feeders this resulted in undervoltages and overloads even before the addition of EV chargers. This will be referred to as the uncalibrated case. Since interest is on the impact of EV chargers on the network, the proportion of additional under-voltages and overloads caused by the addition of EV chargers to the network is calculated (Total violations-Violation without EVs), called calibrated results.

For a given penetration level of EV chargers, the location along the feeders of where the EV chargers will be installed in the future (which ICPs will get an EV) is unknown. Therefore any particular distribution will invariably be wrong. However, by allocating the positions statistically and simulating many possible scenarios (in a Monte Carlo type of simulation) most of the credible combinations should be assessed. This process is depicted in Figure 29. Figure 30 displays the individual results from looking at many scenarios. These are uncalibrated in that the Urban-3 (Periphery) network has under-voltages even before the inclusion of EV chargers. Calibrating these results by displaying the under-voltages due to the inclusion of EV chargers gives Figure 31. These are then averaged to give the curves shown in Figure 32. This figure depicts the expectation (mean) impact of the inclusion of EV Chargers on the different types of networks.

Figure 33 gives an overview of the impact of EV chargers on different types of networks for both AC charging systems on top of maximum loading, while Figure 34 shows the same when the loading if 50% of maximum. It is clear from these figures that the City networks can accommodate the EV Chargers easily. The Urban networks do have considerable ability to host EV chargers. At 50% maximum loading all Urban networks could cope with a penetration level of 0.1 with no violations. The issue is near maximum loading for some networks and hence load control to ensure EV charging does not occur at times of system peak demand is desirable.

Figures 35-38 display histograms of the Voltage magnitude that this type of simulation can provide for the different scenarios. Of note is that although under-voltages are evident (<6%) few are below 10% margin, which is the limit for most electronic equipment to operate satisfactorily (ITIC Curve requirement).

The uncalibrated line overloads are displayed in Figures 39-40.

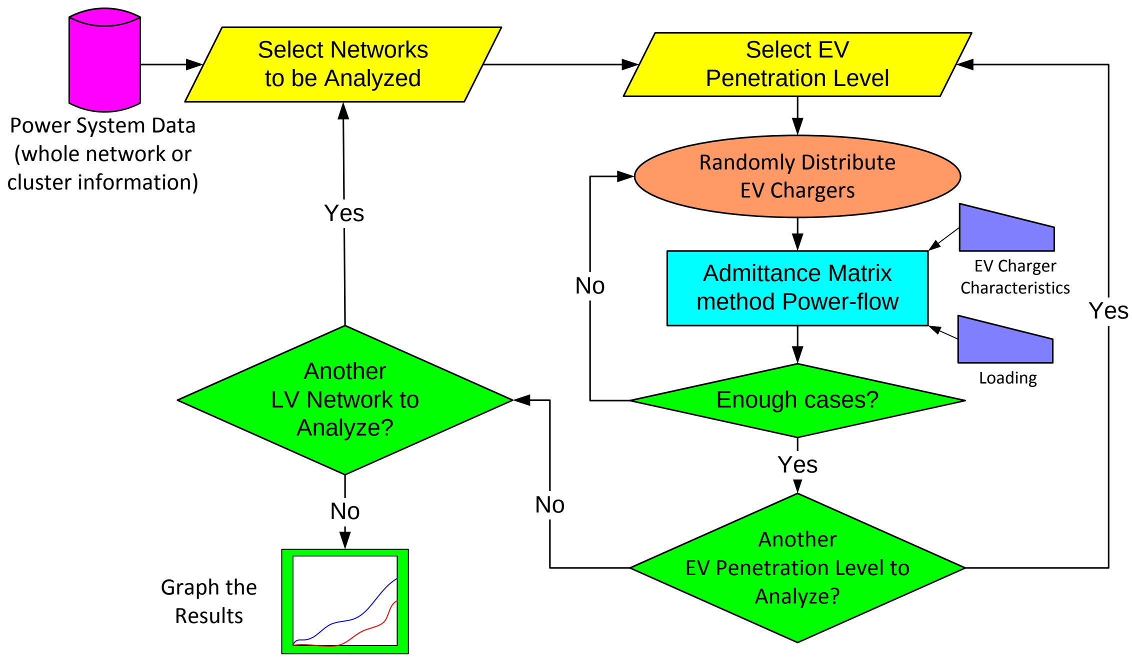

Figure 29. Flowchart of Simulation process

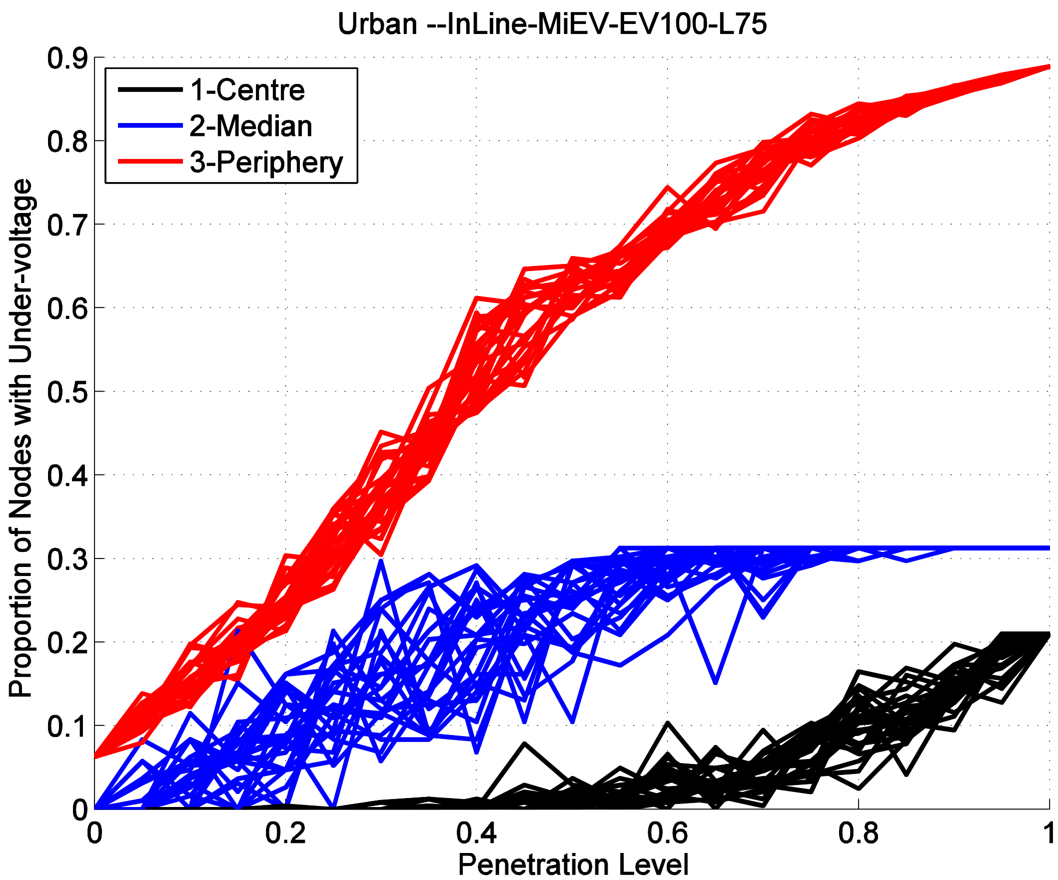

Figure 30. Uncalibrated In-Line Charger with MiEV (75% of Maximum Loading)

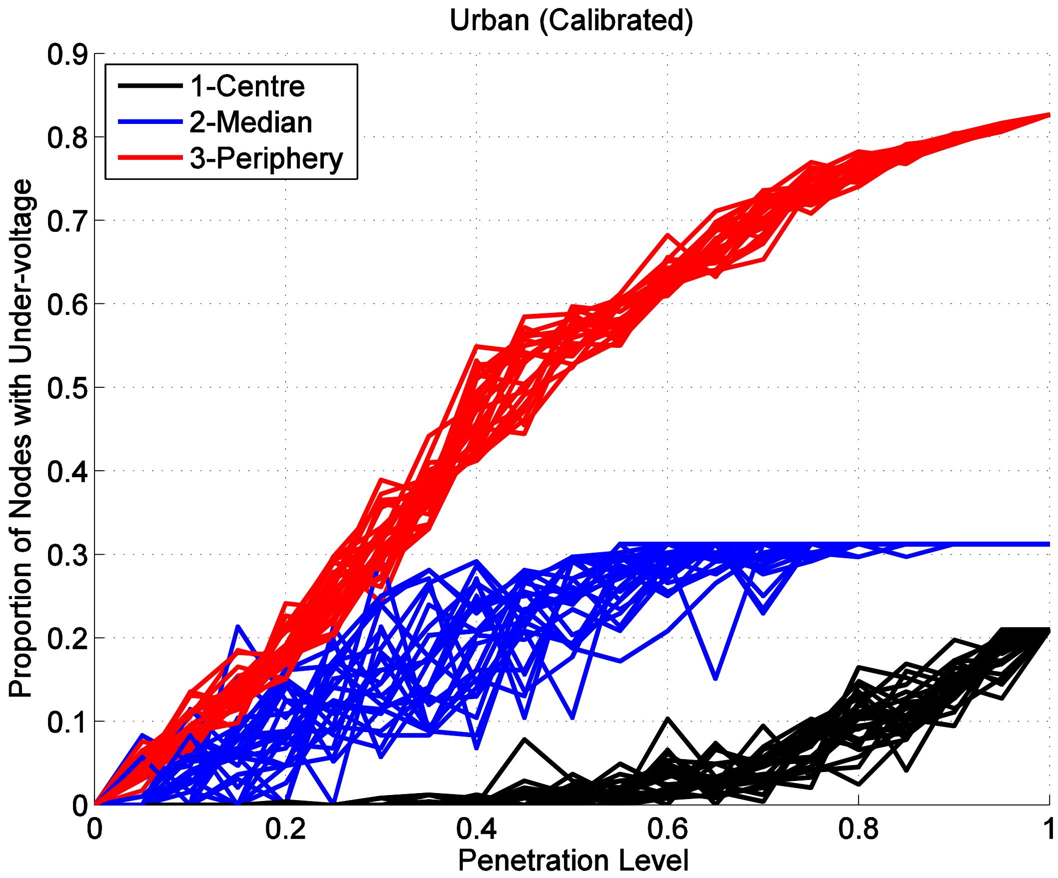

Figure 31. Calibrated In-Line Charger with MiEV (75% of Maximum Loading)

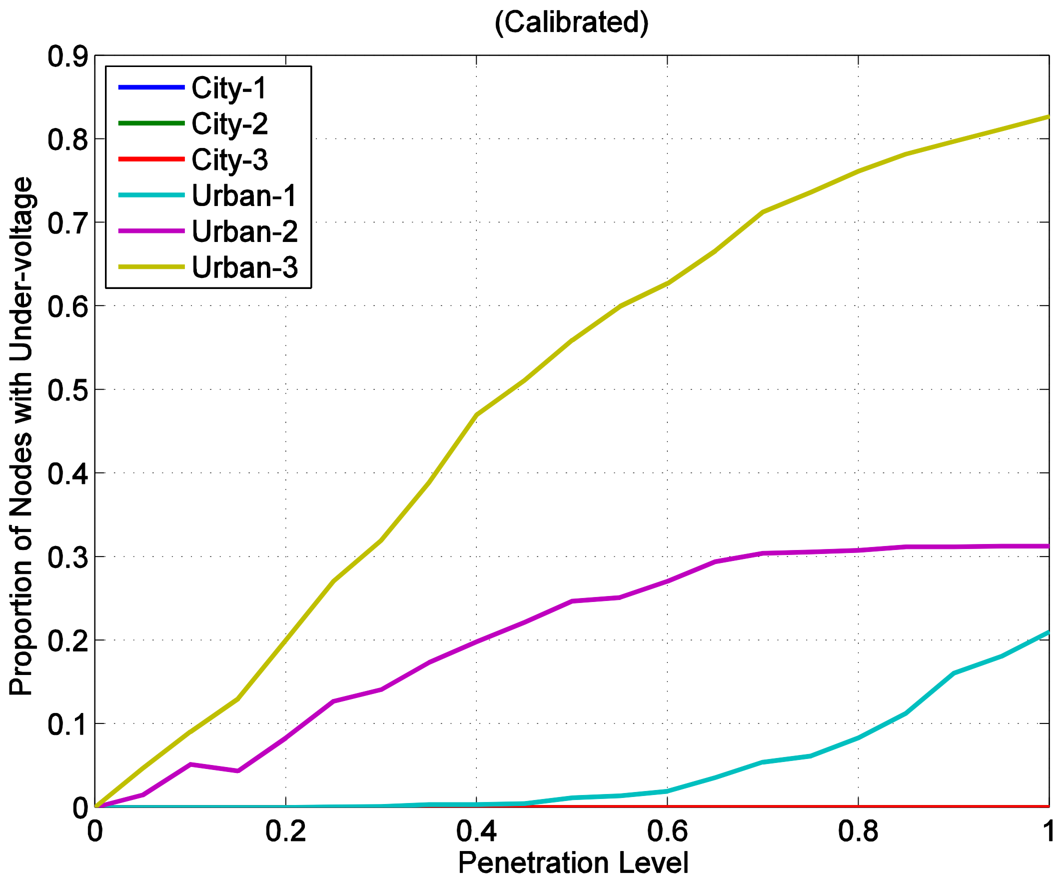

Figure 32. Calibrated In-Line Charger with MiEV (Maximum Loading)

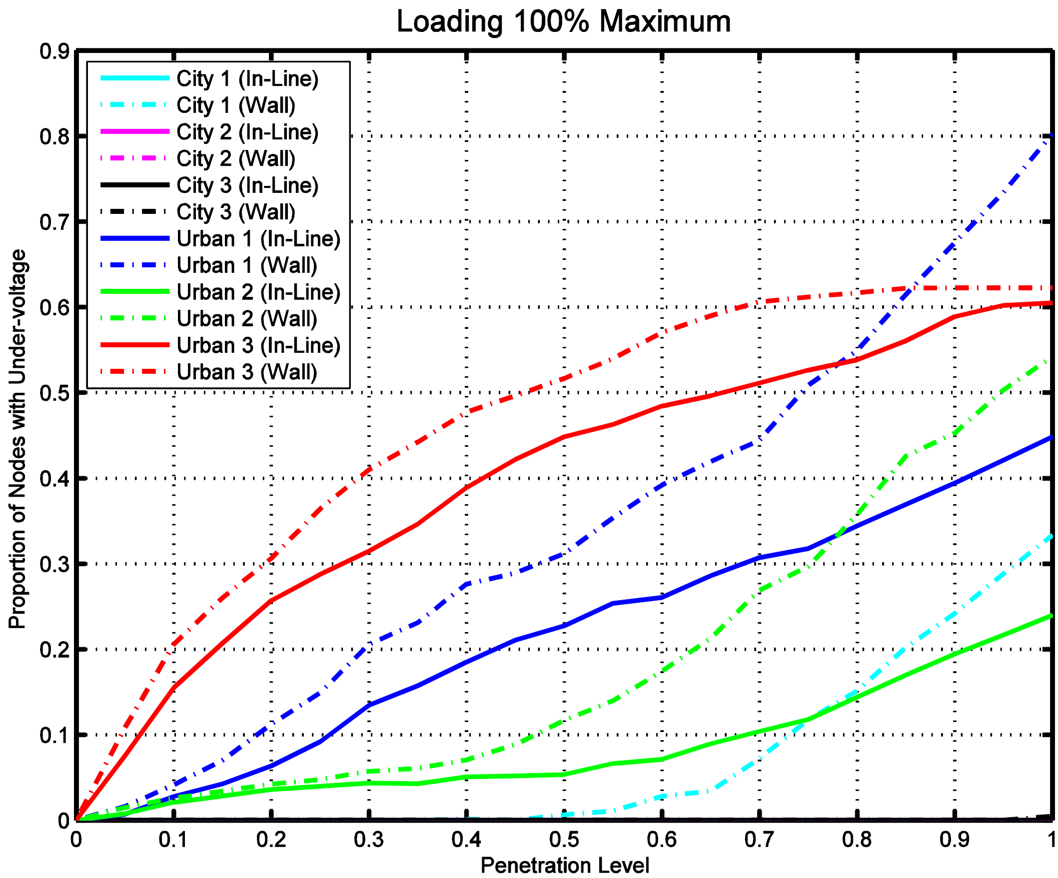

Figure 33. In-Line Charger with MiEV (Maximum Loading)

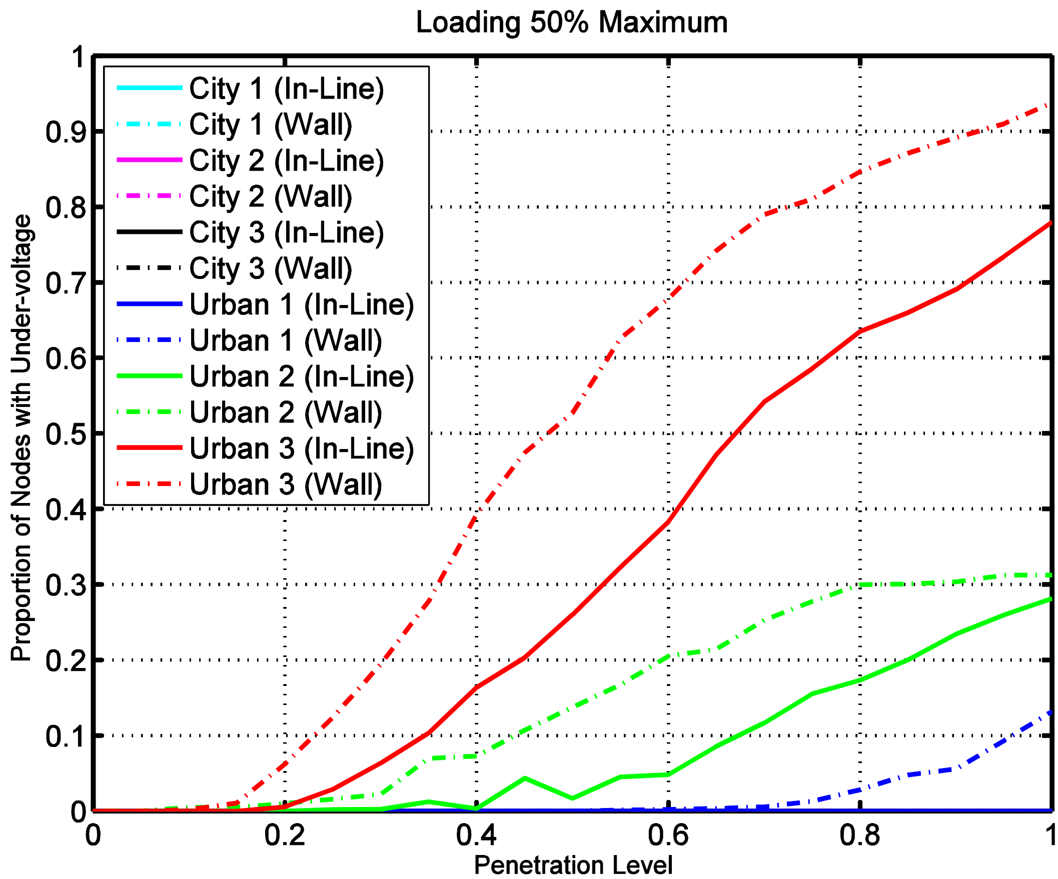

Figure 34. In-Line Charger with MiEV (50%)

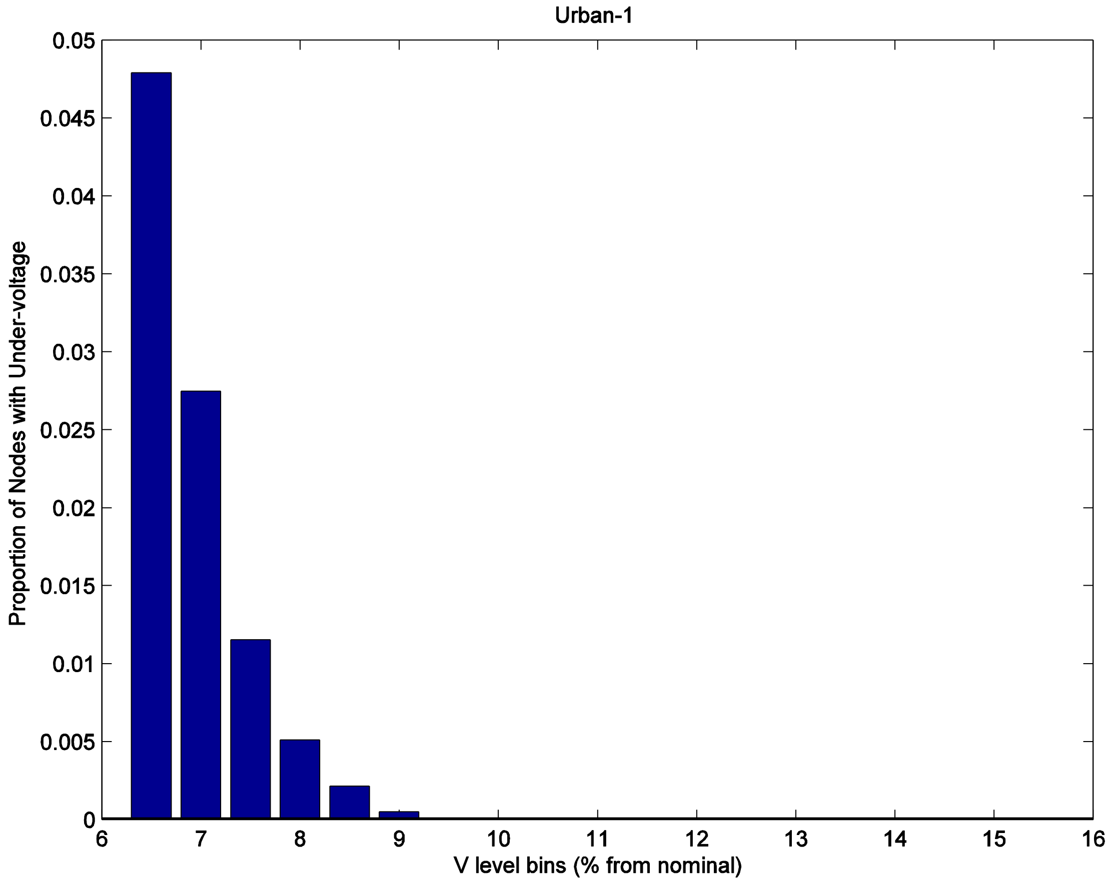

Figure 35. In-line Charger (100% Max Loading and 45% penetration of EVs)

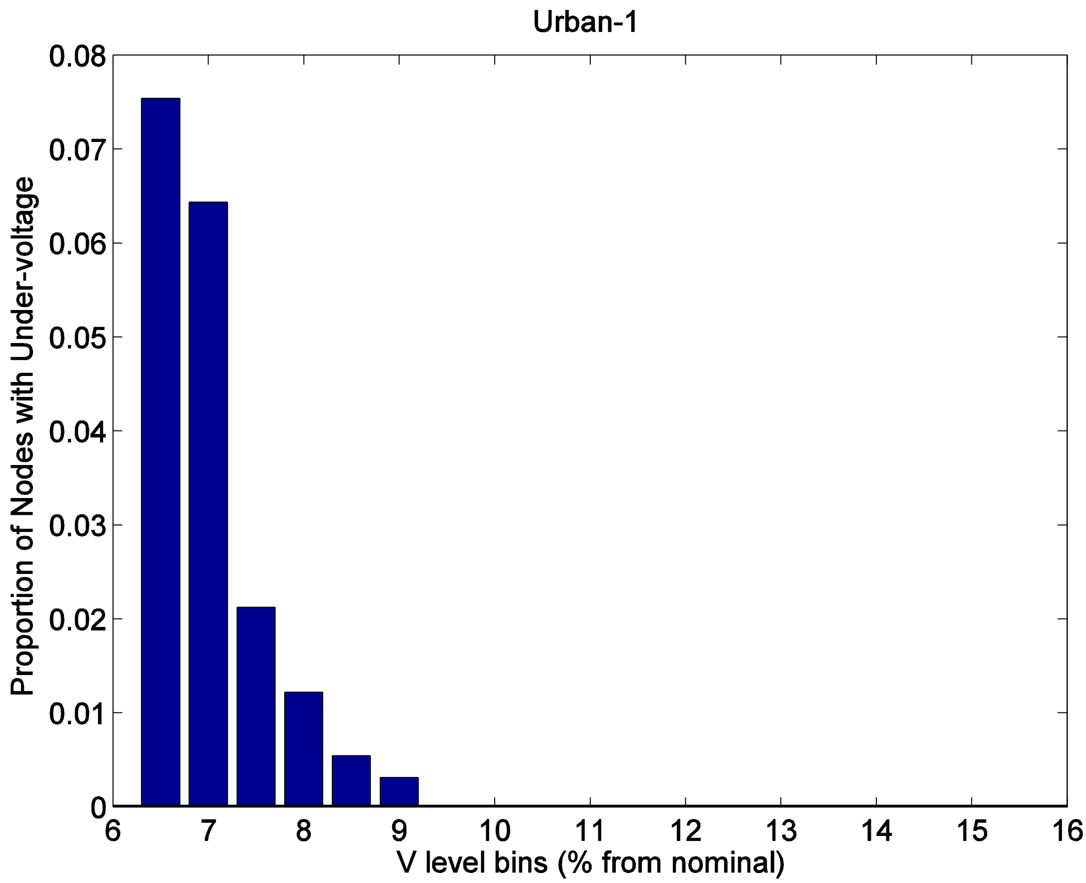

Figure 36. In-line Charger, all penetration levels (75% Max. Loading)

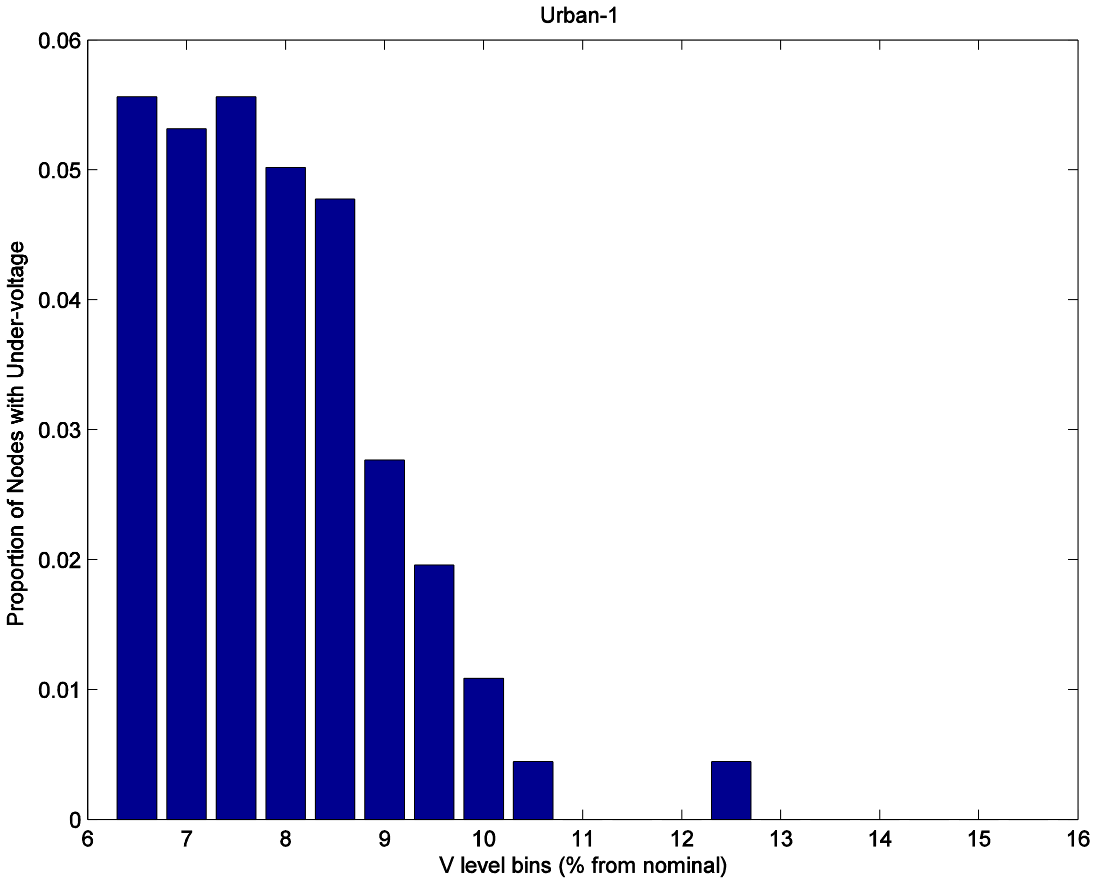

Figure 37. Wall charging system (Maximum Loading, 50% Penetration)

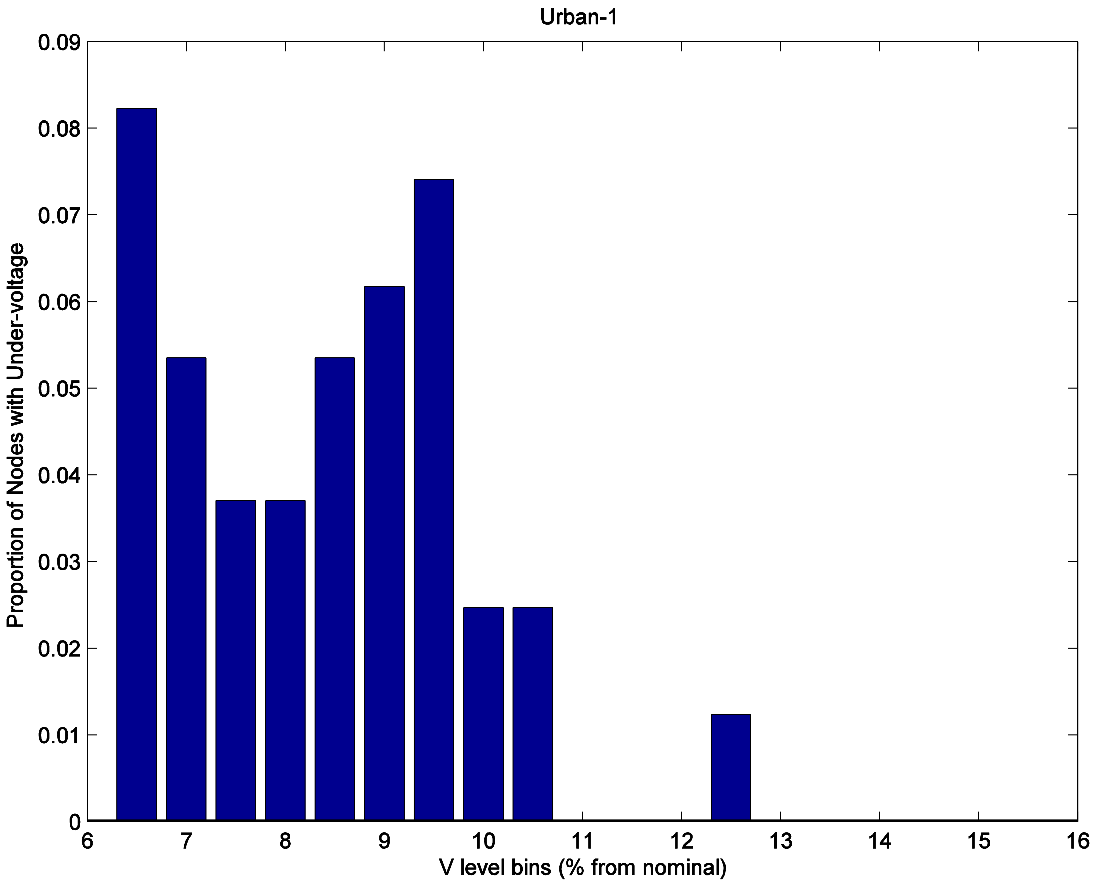

Figure 38. In-line system, All Penetration Levels Combined (Maximum loading)

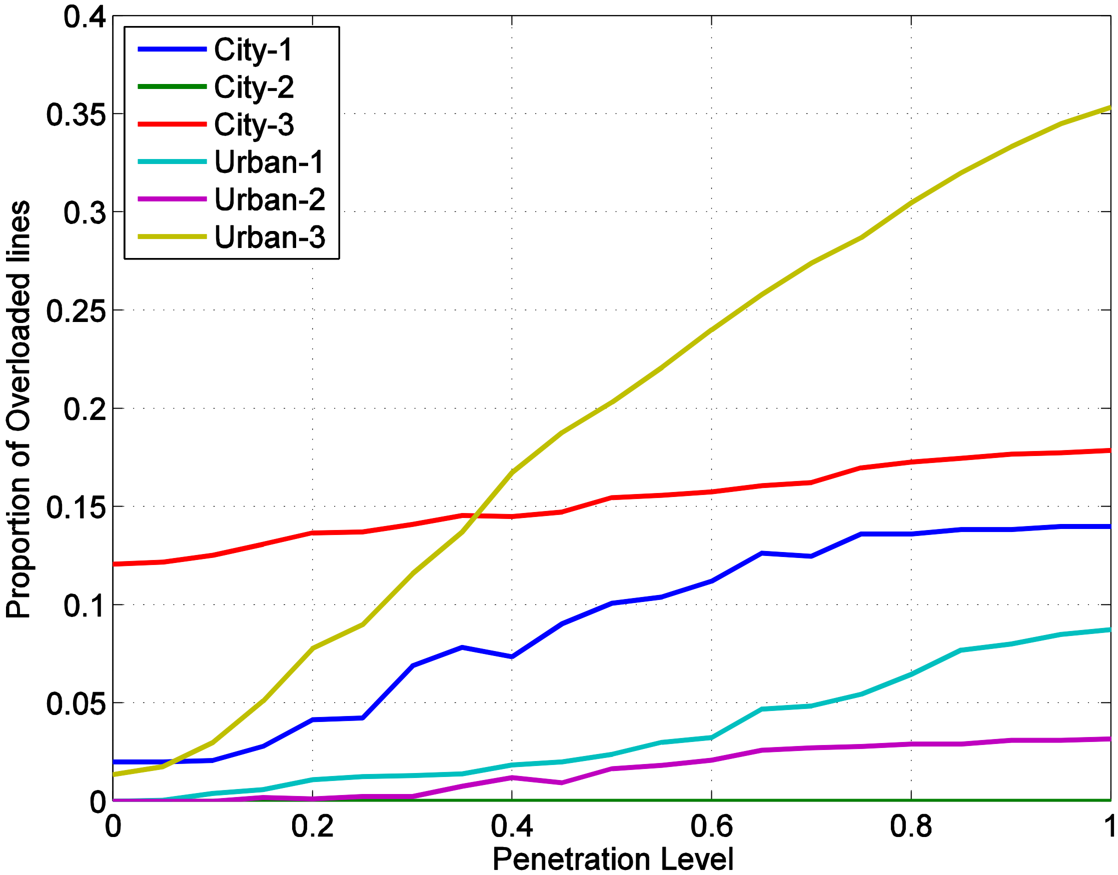

Figure 39. In-line (MiEV), 100% Maximum Loading (uncalibrated)

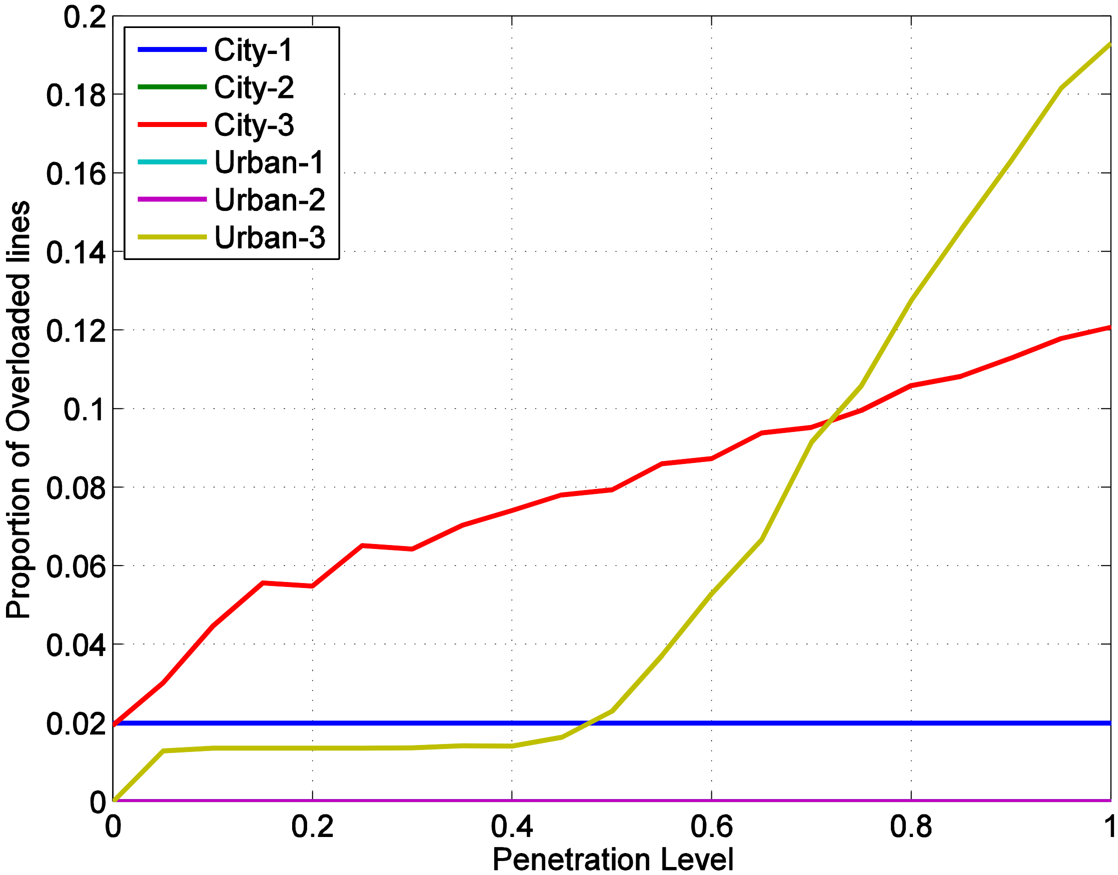

Figure 40. In-line (MiEV), 50% Maximum Loading (uncalibrated)

CONCLUSIONS

The performance of various EV charging systems have been measured in terms of power, current and harmonics and a clearer understanding of the technology has been obtained. This data has been used to model several typical feeders of a New Zealand distribution system to determine the likely impact of wide spread use of EV chargers on a distribution system.

The results show that the New Zealand distribution system is able to cope with the future foreseeable EV penetration levels with few problems. With some type of load control the electrical system can cope with even reasonably high levels of EV penetration.

Due to the variation in strength of the network at different locations, and the nature of the Urban and City networks, it is desirable to limit the charging in the Urban networks to in-line chargers. The results clearly show under-voltage is more of an issue for Urban networks than City networks. Typical urban network (Urban-1) can cope with 40% penetration of in-line chargers without under-voltage issues or line overloading. The City networks are far less susceptible to under-voltage issues. Only the peripheral City-3 network displayed problems with hosting EV chargers, with overloaded lines being the problem.

Simulations for CHAdeMO chargers were not performed because they will never be as widely used as the In-Line and Wall charging systems. First of all CHAdeMO charger requires a three-phase a.c. supply. Secondly, with a power demand of 50-65 kW it should be situated at a place in the network capable of supplying this additional load.

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