Impact of Electric Vehicle Chargers on Harmonic Levels in New Zealand

Jeremy D. Watson
Department of Engineering
University of Cambridge
Cambridge, U.K.
jdw69@eng.cam.ac.uk

Neville R. Watson
Electrical & Computer Engineering Department
University of Canterbury
Christchurch, New Zealand
neville.watson@canterbury.ac.nz

***Abstract*— With the increasing uptake of new technologies such as electric vehicles (EVs), photovoltaic (PV) and wind generation, and LED lighting, there is a need to study their effect on the Power Quality (PQ) of the low voltage (LV) distribution network. These new technologies use power electronic converters which result in harmonics being injected into the AC network. In this paper the impact of EV chargers in terms of harmonic distortion is assessed. The complete LV (400V) network of a distribution company comprising 10,558 11kV to 415V transformers and their associated low voltage distribution feeders, is modelled; and the impact on harmonic levels is determined. The predicted harmonic levels are also considered in a case with photovoltaics and background harmonic distortion, and the levels are compared to the relevant PQ standards and guidelines. Finally, some guidance regarding the practical implications of this work is given.**

Keywords—distributed generation, harmonics; photovoltaic; power quality, renewable generation

I. INTRODUCTION

The desire to reduce greenhouse gas emissions and reduce dependence on imported petroleum are major drivers for the uptake of electric vehicles. New Zealand is ideally placed for the uptake of EVs as approximately 80% of the electricity generation is already from renewable resources. This is in contrast to the many countries where fossil fuels are predominantly used for electricity production, hence any increase in loading will result in more fossil fuel being used. Moreover, the use of renewable energy is increasing in New Zealand, and globally, as a result of increasing deployment of solar photovoltaic (PV) generation and wind generation.

The charging of EVs has the potential to affect the low voltage (LV) distribution system. Ongoing studies have been conducted into the implications for the electrical network of widespread deployment of EV chargers. The main concerns have been undervoltage at customer connections and overloading of feeders and transformers, and these have been addressed in many earlier contributions [1-23]. However, EV rectifiers also generate harmonic currents which flow through the electrical network distorting the voltage waveform. The questions that must be resolved are: how significant are these harmonics, and what is the likely increase in harmonic voltage levels. It is important to understand the likely impacts so that the deployment of EVs can be performed in a cost effective manner. Furthermore, this hosting may be different for the various types of LV networks (urban/residential, city, rural or industrial).

Previous studies on harmonic levels due to EVs have either considered a small representative distribution feeder or system [23-26], or undertaken power quality measurements on a system with EV charging occurring [26-27]. The former does not show the magnitude of the possible problems associated with widespread uptake of EVs as the proportion of the distribution system represented by the typical feeder is unknown. The latter is only applicable to the system investigated and it is difficult to make any conclusions regarding other networks. In order to provide large-scale representation of the many different types of LV networks, this paper presents a simulation case study of the entire low voltage network from a single utility, comprising 10,558 11kV to 415V transformers and their associated low voltage distribution feeders, including all lines, cables and loads. This gives a statistical view of the expected harmonic voltage levels with widespread use of EV, which allows informed decisions and predictions to be made.

In general, the five factors that limit hosting capacity of EV chargers are: (i) steady-state voltage, (ii) thermal limits of lines, cables and transformers, (iii) voltage unbalance, (iv) voltage distortion and (v) voltage fluctuations. Factors (i)-(iii) are all fundamental frequency issues that have already been addressed. In this paper, we consider issue (iv) in depth. The rest of the paper is organized as follows: section II presents the methodology of the simulation study; section III presents the simulation results, firstly for a simplified case without background harmonics, then with household background harmonics, and finally PV harmonic injections are considered in conjunction with EV and background harmonics. Finally, section IV presents the conclusions of the study.

II. METHODOLOGY

This work builds on the previous fundamental frequency model [1]. Various EV penetration levels are considered and a Monte Carlo simulation is performed to determine the expected harmonic levels. Monte Carlo simulation is required as which premises on the network is unknown are EV charging sites and hence a number of different scenarios are analysed and the statistical results obtained. Moreover, the type of EV at each applicable site is randomly allocated and a lookup table of measured harmonics used. The flow-chart of the process is shown in Fig. 1 and this follows the same approach as used for PV harmonic assessment in [28].

The program was executed on MATLAB. The statistical results are presented for the whole system, as well as by network type based on using the k-means clustering technique. Details of

978-1-5386-4950-3/17/$31.00 ©2017 IEEE

the clustering can be found in [1]. The harmonic current injections are based on EV charger test results.

The measured harmonic currents are given in Appendix A. This data was obtained from a public EV charging station and hence included background harmonics. A current injection method is utilised where a system of linear equations, of the form in (1) is set up for each harmonic order. Reactances are scaled by the harmonic order h, and the resistances by $\sqrt{h}$ to represent their frequency dependency [29]. These equations are solved for the harmonic voltages voltages (V_h), given the current injection (I_h) and the network harmonic admittance matrix [Y_h].

$$I_h = [Y_h]V_h \quad (1)$$

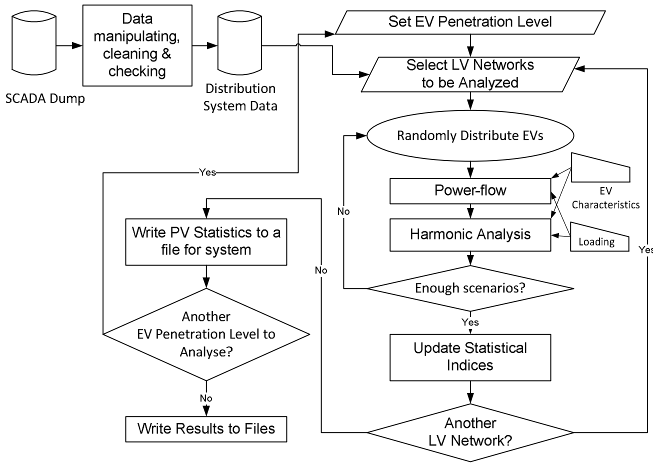

Fig. 1. Flow-chart of process

The harmonic penetration analysis for the network gives an upper bound of the increase in harmonic voltages due to the widespread deployment of EVs. It is an upper bound as it ignores possible diversity between the harmonics injected by the EVs and harmonic injection from other sources (in this case homes). Hence the simulations results are conservative, i.e. considering the worst case.

III. Simulation Results

A. *Complete Distribution System (no Background Harmonics)*

As previously mentioned, the simulation results give the harmonic voltage caused by the EV chargers and must be viewed in light of background harmonics from other harmonic sources as well as the planning levels for voltage harmonics. For reference the Electricity Engineers' Association of New Zealand (EEA) Power Quality (PQ) Guidelines give indicative planning values of 4.5% (3rd), 5.4% (5th), 4.5% (7th) and 2.7% (9th) [20].

Fig. 2 shows the CP95 harmonic levels for the whole system as a function of the EV penetration level, whereas Fig. 3 displays the indices for the 3rd harmonic only. A box-plot of the statistics for the whole distribution system with 50% EV penetration is displayed in Fig. 4. The central mark in each box indicates the median, while the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers by the MATLAB function. Outliers are plotted individually using the '+' symbol. From these results, it is clear that the triplen harmonic voltages are considerably higher than the non-triplen due to the higher triplen harmonic currents injected.

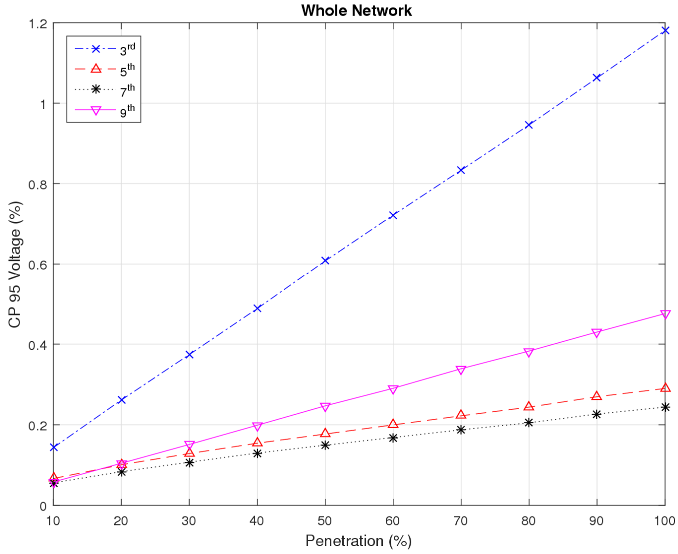

Fig. 2. CP95 levels for complete distribution system

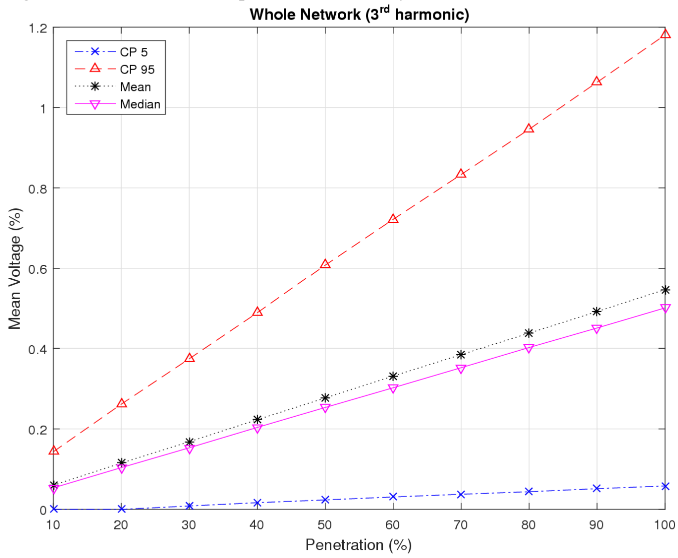

Fig. 3: 3rd harmonic for complete distribution system

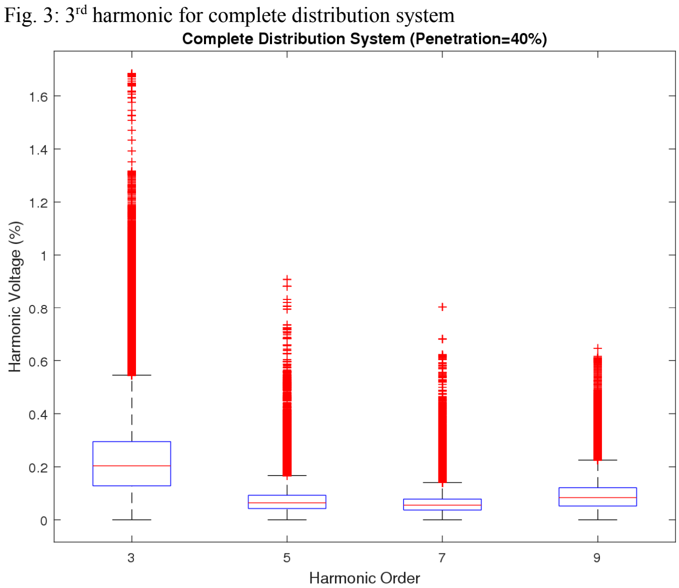

Fig. 4: Box plot for complete distribution system

B. Complete Distribution System (Background Harmonics)

The previous simulations looked at the contribution of the EV charger harmonics in isolation. There are many other sources of harmonics however and the net effect is not simply the arithmetic sum of these and the EV harmonics due to diversity. There are two aspects to diversity, time diversity (i.e. the variation in harmonic emissions with time) and diversity in phase angle of the injected harmonics. The last factor is particularly important as harmonic sources can cancel each other out, resulting in lower network harmonic distortion [22].

Hence, background harmonic measurements from various residential sites in the network were included in the model. To capture both diversity effects, three suburban houses were monitored for 2 to 3 weeks each. From these measurements, 15 sample points representing a range of loading conditions was taken. For each load in the network a random integer was generated using a uniform probability distribution, to specify which of these 15 measured harmonic currents was to be injected into the simulated network. The harmonic current injected by devices into the network is influenced by the voltage distortion on the devices terminals. Although the effect of the network distortion on load harmonic current injections is not captured, this effect is minor compared to the diversity effects previously mentioned. Since each LV network is analysed independently, the calculated harmonic voltages on the Medium Voltage (MV), i.e. 11 kV, network, are due to that LV network in isolation, not including the distortion due to the other LV networks connected to the MV system. The MV distortion levels are considerably lower than in the LV due to the significant harmonic voltage across the 11kV/415V transformer.

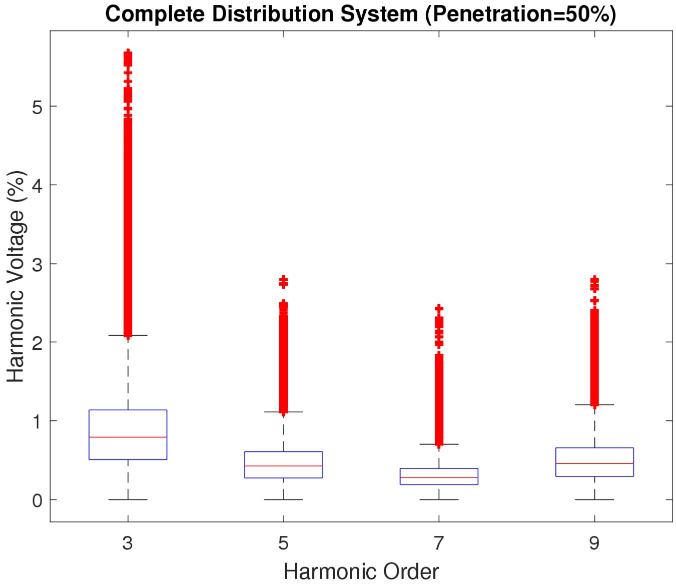

Fig. 5: Box plot for complete distribution system (EV + Background distortion)

Box-plots of the results are displayed in Figs. 5-9 for 50% EV penetration. Note the relatively large magnitude of 3rd & 9th harmonic, which is different to the case of PV inverter harmonics in which the 7th is dominant. Residential/urban networks show the greatest susceptibility to EV charger harmonics and yet have the biggest potential for EV uptake. City networks contain small distances between customer connection points (sometimes called installation control points or ICPs) and hence the magnitude of the harmonic voltages is lesser. As expected, industrial networks can accommodate a far larger harmonic injection from EV chargers. Rural LV networks are normally relatively small (supplying one farm or sometimes only part of a farm). The LV feeder length can be considerable, running from the transformer on the roadside to the point of use, or very short when an 11 kV cable is taken into the farm, and the transformer is ground mounted next to the major load (such as an irrigation pump). This combination of LV systems results in the harmonic voltages being under half those of an urban system.

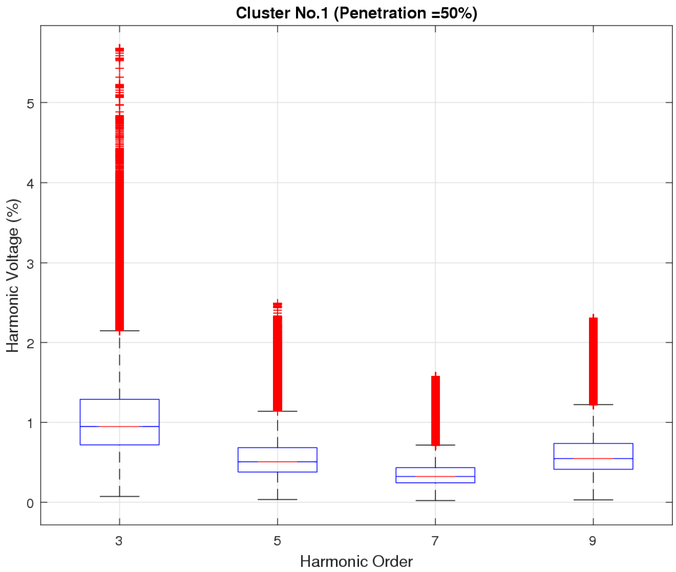

Fig. 6: Box plot for Residential/Urban networks

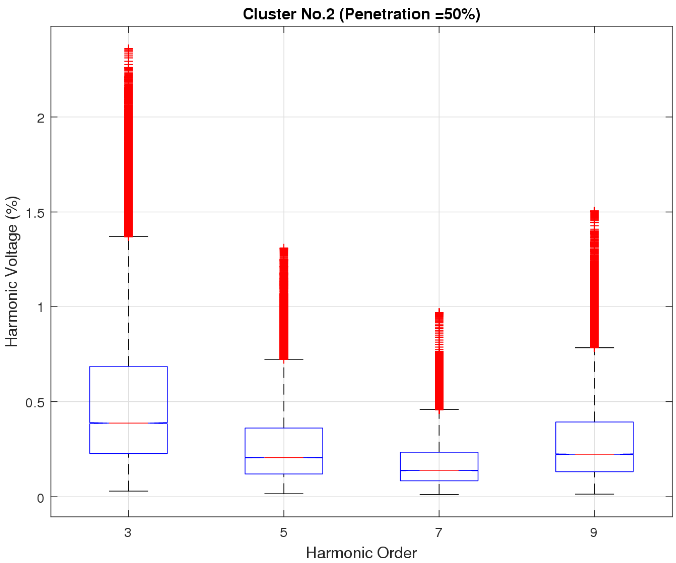

Fig. 7: Box plot for City networks

A comparison of the harmonic levels without and with background distortion (BD) is shown in Fig. 10 for an EV penetration level of 50%. This shows that the background distortion has significantly contributed to the harmonic voltage levels. The CP 95 levels are plotted as a function of penetration level in Fig. 13. The 3rd harmonic level continue to increase with an increasing penetration levels of EV, as does the 9th harmonics. On the other hand the 5th and 7th harmonic voltage levels remain the same regardless of the EV penetration level.

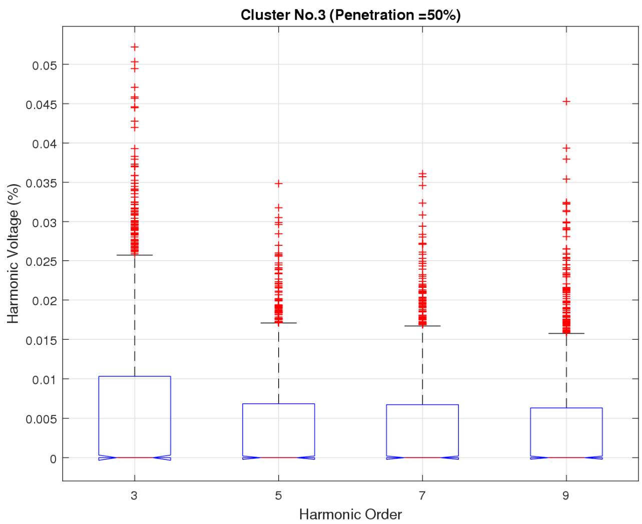

Fig. 8: Box plot for Industrial networks

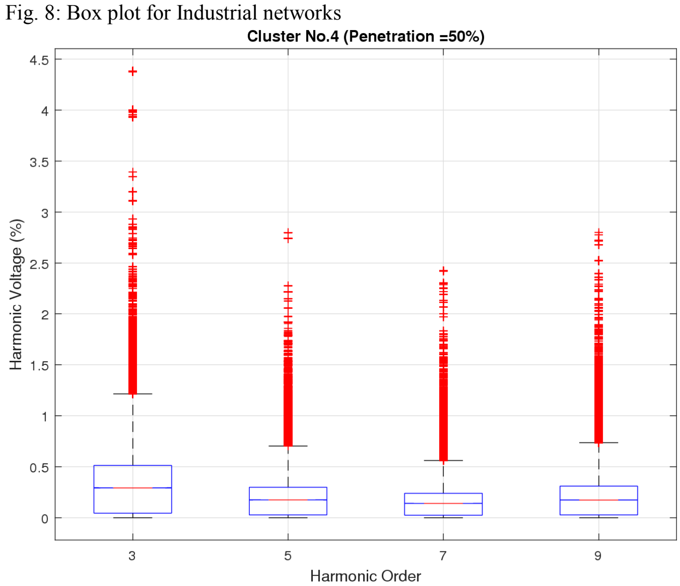

Fig. 9: Box plot for Rural networks

There have been research contributions using power electronic converters to perform their primary function and phase the harmonics in order to lower the voltage distortion. A hypothetical scenario was simulated where the harmonic phase angles of the injected currents from the EV charger were changed by 180° [30]. The results for this are shown in Fig. 11. This type of analysis allows analysis in detail of each LV system in the distribution system. This is illustrated in Figs. 12 & 13 for one LV network (see [28] for schematic of this LV system). To clearly see the contribution the EV harmonics over the background levels, Fig. 14 shows the CP95 level for; EV + BD, EV only & with BD only. The latter (BD only) is flat as expected. Clearly the 3^{rd} and 9^{th} harmonic voltages are significantly influenced by the EV chargers.

C. Complete Distribution System (Background + PV harmonics)

For CO_2 emissions to reduce, electricity production needs to be from renewable resources, hence the interest in PV generation as well as having EVs. The question that is how the PV inverter harmonics and the EV charger harmonics interact together with the background harmonics and influence the network's harmonic voltage levels.

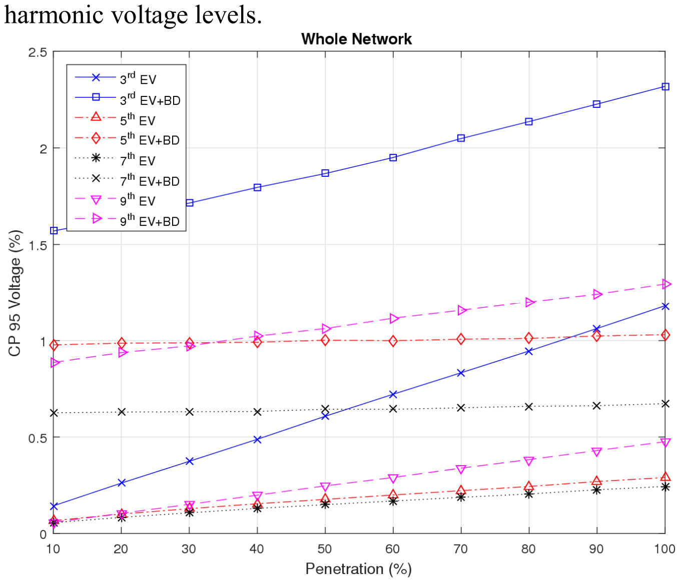

Fig. 10: Plot of harmonics with and without background harmonics

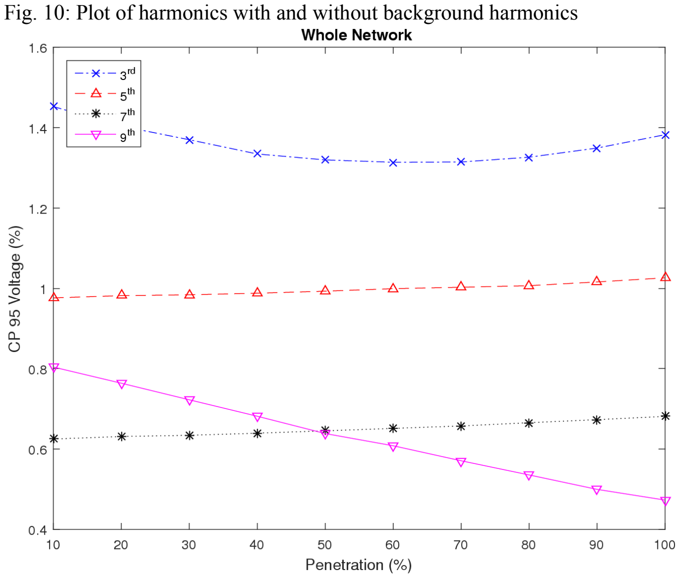

Fig. 11: Plot of harmonics with EV charger harmonic phase angles reversed

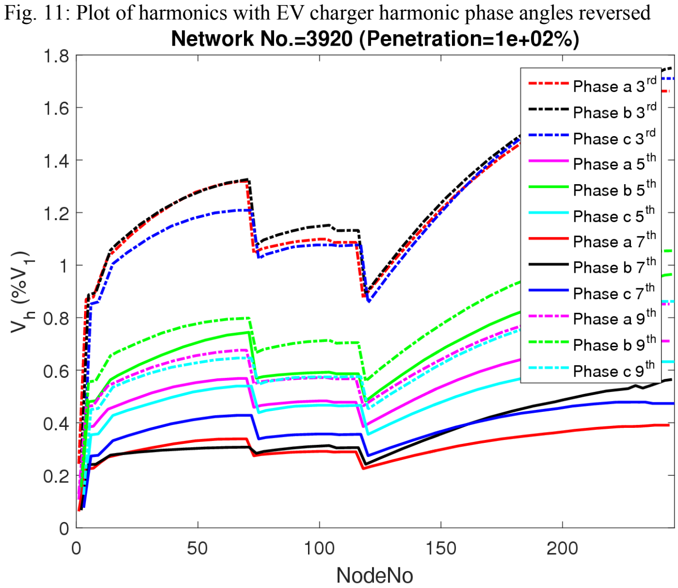

Fig. 12: Profile of harmonic voltages on LV system 3920

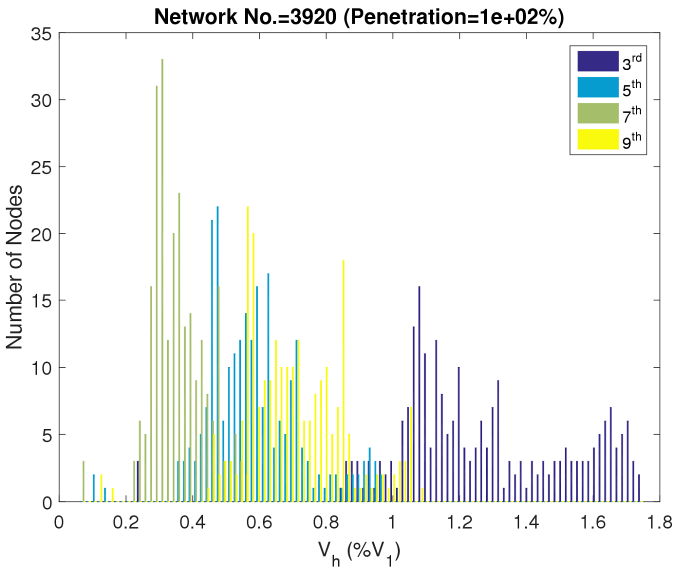

Fig. 13: Histogram of harmonic voltages on LV system 3920

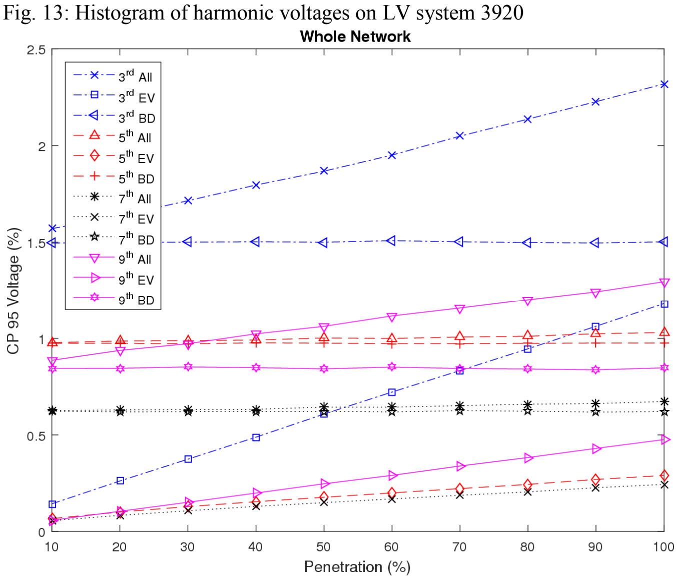

Fig. 14: CP95 level for (i) EV + BD, (ii) EV only & (iii) BD only

All three sources of harmonics have been modelled and the combined effect is shown in Figs. 15 & 16. For this simulation 40% penetration of PV systems and 50% penetration of EVs was assumed. The 3rd and 5th harmonic voltages drop with the addition of the PV inverter harmonics, indicating that these cancel some of the background & EV harmonics. The 7th and 9th harmonic voltages increase indicating a reinforcement.

IV. Discussion & Conclusions

When considering EV deployment, detailed modelling is not practical due to the uncertainty of which residences will be sites of EV charging. To overcome this the sites were randomly selected, and a number of different EV charging scenarios were considered and the results combined to give an overall picture of the likely impact. The purpose was to determine what are the constraining factors for widespread EV deployment. It is clear that it is not the harmonic levels.

Previous work showed that for urban networks 40% was the penetration level when transformers start to become overloaded (the number rapidly raising after 40%) [1]. This is understandable as these transformers have a certain amount of reserved capacity for future growth, but beyond this overloading occurs. An obvious solution is to consider the timing of charging more carefully (i.e. charging at times when the system loading is low and staggering the EV charging).

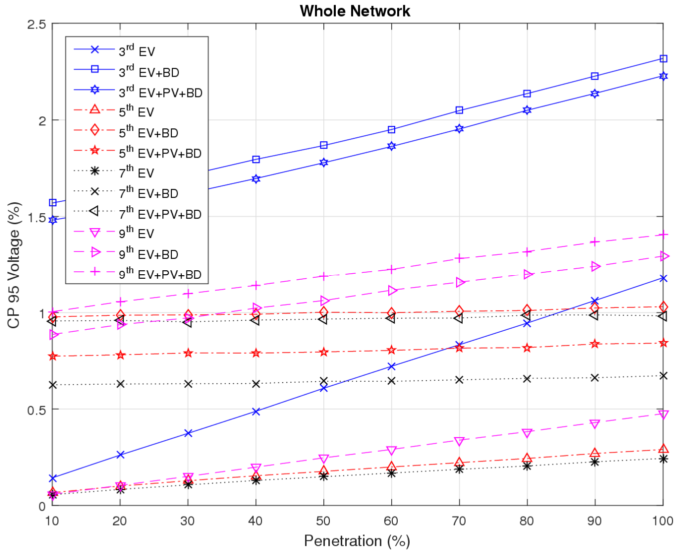

Fig. 15: CP95 level for (i) EV only, (ii) EV+BD & (iii) EV+PV+BD

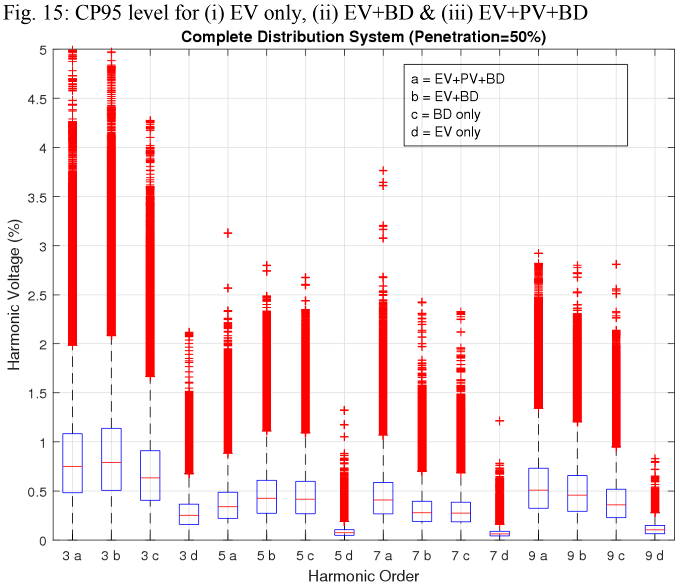

Fig. 16: CP95 level for (i) EV only, (ii) EV+BD & (iii) EV+PV+BD

These simulations have given an indication of the anticipated harmonic voltage levels due to electric vehicle charging. Comparing these levels with the harmonic limits indicate they are well within them [31-32]. The measured harmonic characteristics of the electric vehicle's on-board charger have been used for the simulation (see Appendix). The EV's on-board charger can draw a variety of power level based on the charging system it is plugged into. In New Zealand 10 S, 16 A & 32 A systems exist, however, a standard 10 A in-line charging system used in a residential installation was modelled (except for the Tesla S). The following conclusions can be drawn from these results and the previous work [1]:

- The EV hosting capacity is limited by fundamental frequency issues rather than harmonic distortion.
- The harmonic voltage levels will not result in regulatory levels being breached (unless there is a harmonic resonance).
- The 3rd is the dominant harmonic followed by the 9th.

REFERENCES

[1] N.R. Watson, J.D. Watson, R.M. Watson *et al*, "Impact of Electric Vehicle Chargers on a Low Voltage Distribution System, EEA Conference & Exhibition, 24-26 June 2014, Wellington, 2015
[2] A. Shortt and M. O'Malley, "Quantifying the Long-Term Impact of Electric Vehicles on the Generation Portfolio," *IEEE Trans. on Smart Grid*, vol. 5, no. 1, pp. 71-83, Jan. 2014.
[3] H. Turker and S. Bacha, "Application of Housing Peak Shaving (HPS) algorithms with Plug-in Hybrid Electric Vehicles (PHEVs): Impacts on the aging rate of low voltage transformer," 2015 IEEE Transportation Electrification Conf. and Expo (ITEC), Dearborn, MI, 2015, pp. 1-6.
[4] C. H. Tie, C. K. Gan and K. A. Ibrahim, "The impact of electric vehicle charging on a residential low voltage distribution network in Malaysia," 2014 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), Kuala Lumpur, 2014, pp. 272-277.
[5] R. A. Verzijlbergh, Z. Lukszo, J. G. Slootweg and M. D. Ilic, "The impact of controlled electric vehicle charging on residential low voltage networks," 2011 International Conference on Networking, Sensing and Control, Delft, 2011, pp. 14-19.
[6] L. Pinter, "Statistical analysis of the electric vehicle chargers' impacts on the low-voltage distribution system," 18th Mediterranean Electrotechnical Conference (MELECON), Lemesos, 2016, pp. 1-6.
[7] A. Bosovic, M. Music and S. Sadovic, "Analysis of the impacts of plug-in electric vehicle charging on the part of a real low voltage distribution network," 2015 IEEE Eindhoven PowerTech, Eindhoven, 2015, pp. 1-5.
[8] D. B. de Castro, S. Übermasser, S. Henein, M. Stifter, J. Stöckl and S. Höglinger, "Dynamic Co-simulation of agent-based controlled charging electric vehicles and their impacts on low-voltage networks," IEEE Int. Workshop on Intelligent Energy Systems, Vienna, 2013, pp. 82-88.
[9] P. Richardson, D. Flynn and A. Keane, "Impact assessment of varying penetrations of electric vehicles on low voltage distribution systems," IEEE PES General Meeting, Minneapolis, MN, 2010, pp. 1-6.
[10] A. T. Procopiou, J. Quirós-Tortós and L. F. Ochoa, "HPC-Based Probabilistic Analysis of LV Networks With EVs: Impacts and Control," in IEEE Trans. on Smart Grid, vol. 8, no. 3, pp. 1479-1487, May 2017.
[11] Z. Qiao and J. Yang, "Low-voltage distribution network reconfiguration considering high penetration of electric vehicles; A UK case study," 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, 2016, pp. 708-713.
[12] J. D. Cross and R. Hartshorn, "My Electric Avenue: Integrating electric vehicles into the electrical networks," 6th Hybrid and Electric Vehicles Conference (HEVC 2016), London, 2016, pp. 1-6.
[13] J. Meyer, A. M. Blanco, M. Domagk and P. Schegner, "Assessment of Prevailing Harmonic Current Emission in Public Low-Voltage Networks," *IEEE Trans. on Power Delivery,* vol. 32, no. 2, pp. 962-970, April 2017
[14] X. Yan, C. Gu and F. Li, "Value quantification of electric vehicle response on network investment in the UK," IEEE PES Innovative Smart Grid Technologies Conf. Europe (ISGT-Europe), Ljubljana, 2016, pp. 1-5.
[15] A. Hoke, *et al,*, "Steady-State Analysis of Maximum Photovoltaic Penetration Levels on Typical Distribution Feeders," *IEEE Trans. on Sustainable Energy,* vol. 4, no. 2, April 2013, pp. 350-357
[16] C. Gonzalez, J.Geuns, *et al*, "LV distribution network feeders in Belgium and power quality issues due to increasing EV penetration levels," *3rd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe)*, 2012, pp. 1-8
[17] P. Trichakis, *et al*, "Predicting the technical impacts of high levels of small-scale embedded generators on low-voltage networks," *IET Renewable Power Generation*, vol. 2, no. 4, 2008, pp. 249-262
[18] R. Walling, *et al*, "Summary of Distributed Resources Impact on Power Delivery Systems," *IEEE Trans. on Power Delivery*, vol.23, no.3, 2008, pp. 1636-1644
[19] M. Thomson and D.G. Infield, 2007, "Impact of widespread photovoltaics generation on distribution systems," *IET Renewable Power Generation*, vol. 1, pp. 33–40, 2007
[20] C. Tie, and C. Gan, "Impact of grid-connected residential EV systems on the Malaysia low voltage distribution network," *IEEE 7th Int.Power Engineering and Optimization Conference*, Malaysia, 2013, pp. 670-675
[21] R. Tonkoski, D. Turcotte and T. El-Fouly, "Impact of High EV Penetration on Voltage Profiles in Residential Neighborhoods," *IEEE Trans. on Sustainable Energy*, vol. 3, no.3, 2012, pp.518-527
[22] Z. Jiang, H. Tian, M. J. Beshir, R. Sibagatullin and A. Mazloomzadeh, "Statistical analysis of Electric Vehicles charging, station usage and impact on the grid," IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Minneapolis, MN, 2016, pp. 1-5.
[23] C. Jiang, R. Torquato, D. Salles and W. Xu, "Method to Assess the Power-Quality Impact of Plug-in Electric Vehicles," in IEEE Transactions on Power Delivery, vol. 29, no. 2, pp. 958-965, April 2014.
[24] V. Monteiro, H. Gonçalves and J. L. Afonso, "Impact of Electric Vehicles on power quality in a Smart Grid context," 11th International Conference on Electrical Power Quality and Utilisation, Lisbon, 2011, pp. 1-6.
[25] A. Supponen, A. Rautiainen, J. Markkula, A. Mäkinen, P. Järventausta and S. Repo, "Power quality in distribution networks with electric vehicle charging - a research methodology based on field tests and real data," 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER), Monte Carlo, 2016, pp. 1-11.
[26] Q. Li, S. Tao, X. Xiao and J. Wen, "Monitoring and analysis of power quality in electric vehicle charging stations," 2013 1st International Future Energy Electronics Conference (IFEEC), Tainan, 2013, pp. 277-282.
[27] R. J. C. Pinto, J. Pombo, M. R. A. Calado and S. J. P. S. Mariano, "An electric vehicle charging station: Monitoring and analysis of power quality," 2015 9th International Conference on Compatibility and Power Electronics (CPE), Costa da Caparica, 2015, pp. 37-42.
[28] J.D. Watson and N.R. Watson, "Impact of Residential PV on Harmonic Levels in New Zealand", IEEE Int. Conf. on Innovative Smart Grid Technologies, IEEE ISGT Europe 2017, Torino (Italy), 26-29 Sept. 2017
[29] J. Arrillaga, B.C. Smith, N.R. Watson and A.R. Wood, "Power System Harmonic Analysis," *John Wiley & Sons*, 1997.
[30] D. Rentoul, "A single-phase bi-directional H-bridge converter with harmonic filtering capabilities", Masters Thesis, University of Canterbury, 2004.
[31] N.R. Watson, "Power-Quality Management in New Zealand," IEEE Trans. on Power Delivery, vol. 31, no. 5, 2016, pp. 1963 – 1970
[32] EEA N.Z., "EEA Power Quality (PQ) Guidelines," 2013, https://www.eea.co.nz/tools/products/details.aspx?SECT=publications&ITEM=2577-100.

APPENDIX: EV CHARGER HARMONIC CURRENTS

Table V. EV charger harmonic current data

	h	Measured data	
		Mag. (A)	Angle (°)
Nissan Leaf (Gen. 1)	3	1.08845	-81.7073
	5	0.127465	-122.195
	7	0.0838	63.4146
	9	0.0700845	-6.09756
Nissan Leaf (Gen. 2)	3	1.0648	-152.439
	5	0.442254	37.8049
	7	0.270423	174.39
	9	0.04366	-94.5122
Nissan Leaf (Gen. 2)	3	1.065	-153.803
	5	0.441	157.606
	7	0.272	52.1127
	9	0.0431	-96.761
Nissan Van	3	1.341	-156.056
	5	0.46761	30.986
	7	0.2721	163.94
	9	0.0676	-130.141
Mitsubishi i-MiEV	3	0.7662	-116.188
	5	0.224648	-98.827
	7	0.03718	-27.9832
	9	0.07031	-67.42
VW eGolf	3	0.3955	-85.07
	5	0.31845	44.761
	7	0.17972	-112.113
	9	0.1442	-46.761
Hyundai Ionqic	3	0.204	52.4
	5	0.1654	90.70
	7	0.2134	-118.87
	9	0.1251	-29.86
Tesla-S (16 A)	3	0.299718	64.79
	5	0.39437	114.366
	7	0.212958	32.113
	9	0.272113	99.718