AN EVALUATION OF V2G FOR DISTRIBUTION NETWORK HARMONIC SUPPRESSION

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ABSTRACT

Vehicle-to-Grid (V2G) is an emerging application of plug-in electric vehicles communicating with power grids to provide energy or ancillary services. Power quality improvement is one of the possible benefits of V2G systems. In this paper, V2G is evaluated as a means to improve distribution network power quality via harmonic suppression. Based on a V2G trial project, simulations were conducted with practical power quality parameters monitored and collected from installed charging points with V2G functions. Both the simulation and practical results revealed an improvement in voltage rms value but an increase in current harmonics during V2G operation. On the other hand, V2G had no significant effect on voltage harmonics. Lastly, potential solutions on how to suppress current harmonics were proposed.

INTRODUCTION

The drive to decarbonise electricity, heat and transport is currently transforming electric power systems globally as large amounts of distributed energy resources (such as PV, wind turbines, battery storage and plug-in electric vehicles – PEVs) are connected at the distribution network level.
These distributed energy resources can export power back to the distribution network and when PEVs are used for this, it is called Vehicle-to-Grid (V2G).

V2G is a concept where energy stored in the battery of a PEV is used to provide grid support or other ancillary services with the consent of the PEV owner and in return for financial incentives. V2G application can provide benefits such as the increased use of localised renewables, energy arbitrage, peak shaving, load balancing, demand response, frequency response and voltage support [1].

Another benefit of V2G is that it can be used to improve power quality on the grid by reducing the harmonics on the network when operated as active power filters [2, 3] but as most Power Electronic Converters (PEC) generate harmonics [4] it may be difficult to justify this approach. Refs [2, 3] carried out simulation studies and showed how harmonics generated from non-linear loads and Electric Vehicle Supply Equipment (EVSE) may be suppressed when the EVSEs are operated in the V2G mode.
However, they did not consider this for different OEM's V2G. In the real world, different OEM's V2G units will have different PEC and harmonic filter configuration. This means each V2G unit will have different harmonic profiles when charging (Grid-to-Vehicle – G2V) or discharging (V2G) an EV. The net effect of this cannot be easily predicted via simulation or via a demonstration using only one OEM's V2G.

In this paper, we aim to evaluate the effect of V2G operation on distribution network harmonics using realistic power networks at two sites in Aston University's campus and as part of the VIGIL (VehIcle to Grid Intelligent controL) project. Both sites have a mix of different OEM's EVSE with V2G capability.

The paper will look at the current and voltage individual harmonics, total harmonic distortion (THD) and total demand distortion (TDD) at several points on the network, and compare this to several international standards (IEEE 519 [5], ENA ER G5/4 [6], IEC 61000-3-2/12 [7]). The paper will explore methods for improving power quality and reducing harmonics on a distribution network via proper sizing of active power filters and/or adapting control schemes of EVSEs in V2G mode.

The outline of the paper is as follows: An introduction is given for the VIGIL project and the two V2G trial sites used for the practical studies on live networks. Then it presents and analyses the MATLAB/Simulink simulation results of the two sites, followed by the presentation of the live trial results for one of the sites. Lastly, it discusses how V2G and active power filters can be used to improve the power quality on a distribution network.

VIGIL PROJECT AND TRIAL SITES

The VehIcle-to-Grid Intelligent controL (VIGIL) project aims to develop, build and trial an off-vehicle control platform (see Figure 1) that aggregates energy at different substations and controls the bidirectional flow of power from Electric Vehicle (EV) batteries with respect to the local substation network constraints and the EV/building energy requirements.

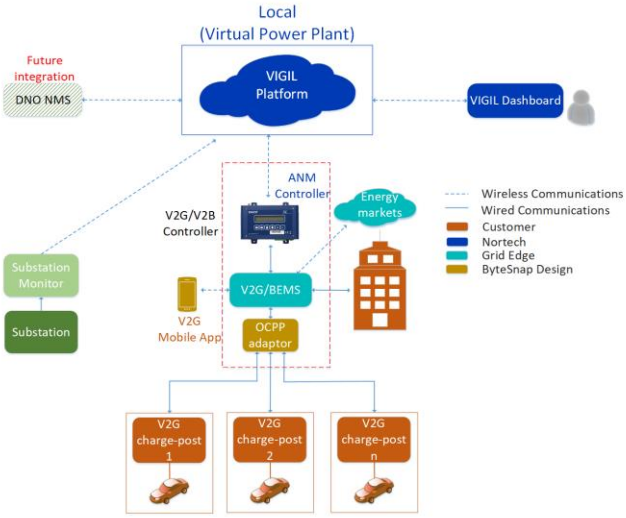

Figure 1: Overview of the VIGIL platform

The project consortium consists of four members. Nortech as project lead is providing the Active Network Management (ANM) scheme that ensures V2G activities are safely carried out without any detrimental effect to the distribution network. Grid Edge is providing the V2G and building energy management solution, ByteSnap is providing the adaptor that ensures the VIGIL platform can communicate with different OEMs' EVSEs, and Aston University is leading the research on V2G power quality and EV battery-life performance as well as providing the two V2G trial sites.

SITE 1: EBRI

The European Bioenergy Research Institute (EBRI) in Aston University is the first trial site for the VIGIL project and the V2G harmonic studies. It comprises two 10kW V2G EVSEs from different OEMs, with one being the first permanent V2G charging system to be installed in the UK. A single line diagram showing parts of EBRI's network used for the harmonic studies is given in Figure 2.

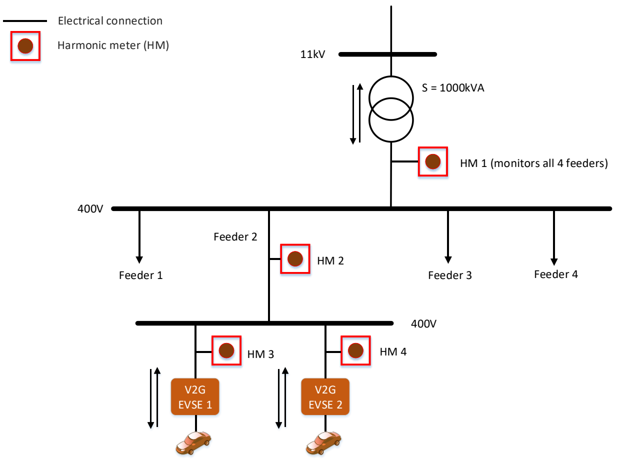

Figure 2: Single-line diagram of EBRI's EVSE network

SITE 2: Car Park 12

Car Park 12 (CP12) in Aston University is supplied by the newly completed Student Guild building which contains large harmonic current sources (such as solar panels). CP12 itself contains six EVSEs (two 10kW V2G EVSEs, one 20kW fast-charging EVSE and three 3.7kW EVSEs). Sections of CP12 network that were used for the harmonic studies are given in Figure 3.

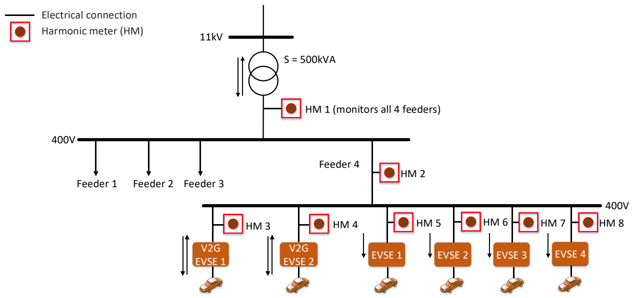

Figure 3: Single-line diagram of CP12 EVSE network

SIMULATION RESULTS

Simulation models for both sites have been implemented in MATLAB/Simulink. Exact parameters of the trial EVSEs are commercially confidential, hence the simulation models were built using standard converter models such as the 2-level PWM voltage source converters for 3-phase EVSEs rated at 10kW and above, diode rectifiers for the single-phase EVSEs, resistive loads and non-linear loads. The simulated EVSE components were sized in accordance with their power rating [8].

SITE 1: EBRI Simulation Results

Results of current and voltage harmonics from the simulation of EBRI's EVSEs measured at HM2 (Harmonic Meter 2) in Figure 2 are given in Tables 1 and 2, respectively. The harmonic values above harmonic standards are highlighted in red and the standards failed are highlighted in yellow.

Table 1: Results of current harmonics, EBRI (simulation)

	G2V	V2G	IEEE 519: 2014	ENA G5/4 (10MVA fault level)	IEC 61000-3-12
I_{rms}	42.84A	15.52A	n/a	n/a	n/a
I_{HD5}	0.24% 0.10A	0.31% 0.05A	4.0%	28.9A	10.7A
I_{HD7}	0.15% 0.06A	0.28% 0.04A	4.0%	41.2A	7.2A
I_{HD11}	0.17% 0.07A	0.28% 0.04A	4.0%	39.4A	3.1A
I_{HD38}	0.93% 0.40A	2.86% 0.44A	0.3%	0.6A (=50th)	n/a
I_{HD42}	0.69% 0.30A	2.12% 0.32A	0.3%	0.6A (=50th)	n/a
I_{THD}	1.38%	3.86%	5.0% (in I_{TDD})	n/a	13%

Table 1 shows an increase in current THD during V2G operation, with a significant rise in current harmonics around the switching frequency of the EVSEs PEC.

Table 2: Results of voltage harmonics, EBRI (simulation)

	G2V	V2G	IEEE 519: 2014	ENA G5/4 (10MVA fault level)	IEC 61000-3-12
V_{rms} (V)	213	224	n/a	n/a	n/a
V_{HD5} (%)	0.06	0.03	5.0	4.0	n/a
V_{HD7} (%)	0.05	0.03	5.0	4.0	n/a
V_{HD11} (%)	0.09	0.05	5.0	3.0	n/a
V_{HD38} (%)	1.78	1.90	5.0	0.2	n/a
V_{HD42} (%)	1.46	1.55	5.0	0.2	n/a
V_{THD} (%)	2.43	2.55	8.0	5.0	n/a

Table 2 shows no significant change in the voltage harmonic content during V2G operation. However, there was improvement in the voltage rms value during V2G as it moves closer to the nominal voltage value of 230V.

SITE 2: Car Park 12 Simulation Results

Results of current and voltage harmonics from the simulation of CP12 EVSEs measured at HM2 (Figure 3) are given in Tables 3 and 4, respectively.

Table 3: Results of current harmonics, CP12 (simulation)

	G2V	V2G	IEEE 519: 2014	ENA G5/4 (10MVA fault level)	IEC 61000-3-12
I_{rms}	72.7A	42.4A	n/a	n/a	n/a
I_{HD5}	3.81% 2.77A	6.83% 2.89A	4.0%	28.9A	10.7A
I_{HD7}	1.86% 1.35A	3.57% 1.51A	4.0%	41.2A	7.2A
I_{HD11}	0.57% 0.41A	1.12% 0.47A	4.0%	39.4A	3.1A
I_{HD38}	0.61% 0.44A	1.15% 0.49A	0.3%	0.6A (=50th)	n/a
I_{HD42}	0.46% 0.33A	0.85% 0.36A	0.3%	0.6A (=50th)	n/a
I_{THD}	4.39%	7.98%	5.0% (in I_{TDD})	n/a	13%

Table 3 presents worse result than that of EBRI. This is because CP12 has more co-located EVSEs. Except for the 7th and 11th current harmonics, all other listed harmonics, including the current THD were above the IEEE 519 standard.

Again, no significant change was noticed in the voltage harmonic content during V2G operation as evident in Table 4. Rather, significant improvement can be seen in the voltage rms value during V2G as it moves closer to the statutory limits (216.2V (-6%) to 253V (+10%) for a nominal voltage of 230V).

Table 4: Results of voltage harmonics, CP12 (simulation)

	G2V	V2G	IEEE 519: 2014	ENA G5/4 (10MVA fault level)	IEC 61000-3-12
V_{rms} (V)	199	211	n/a	n/a	n/a
V_{HD5} (%)	1.84	1.81	5.0	4.0	n/a
V_{HD7} (%)	1.23	1.29	5.0	4.0	n/a
V_{HD11} (%)	0.58	0.64	5.0	3.0	n/a
V_{HD38} (%)	2.11	2.20	5.0	0.2	n/a
V_{HD42} (%)	1.76	1.80	5.0	0.2	n/a
V_{THD} (%)	3.98	3.99	8.0	5.0	n/a

The relationship showed in Tables 1-4 will now be evaluated against the live harmonic data measured at EBRI V2G trial site on Aston University's distribution network.

NETWORK TRIAL RESULTS

SITE 1: EBRI Network Trial Results

Tables 5 and 6 presents the harmonic results from the live V2G EVSE trials at EBRI, measured at point HM2 of Figure 2. It is important to mention that the EVSEs' switching frequency are commercially confidential for the OEMs and hence, are not included in the results. Notwithstanding, we have included the results of the most significant high order harmonic values (29th and 31st harmonic order) measured at HM2.

Table 5: Results of current harmonics, EBRI (practical)

	G2V	V2G	IEEE 519: 2014	ENA G5/4 (10MVA fault level)	IEC 61000-3-12
I_{rms}	138A	115A	n/a	n/a	n/a
I_{HD5}	23% 31.7A	29.1% 33.5A	4.0%	28.9A	10.7A
I_{HD7}	14.8% 20.4A	19.1% 22.0A	4.0%	41.2A	7.2A
I_{HD11}	1.7% 2.35A	1.7% 1.96A	4.0%	39.4A	3.1A
I_{HD29}	0.4% 0.55A	2.0% 2.3A	0.3%	0.6A (=50th)	n/a
I_{HD31}	0.5% 0.69A	1.8% 2.1A	0.3%	0.6A (=50th)	n/a
I_{THD}	28.3%	36.0%	5.0% (in I_{TDD})	n/a	13%

Table 5 shows a trend similar to the simulated results for EBRI. Although, there is high harmonic current content present on the network beyond the IEEE 519 standard, operating the EVSEs in V2G mode further increased the current harmonics. It is important to state that the V2G EVSEs are not the primary cause of the high current harmonic distortion on the network. However, this was included to assess how V2G operation impacts the network's current harmonics. For most applications, EVSEs are embedded in the network and it is the combined harmonics that would be of more interest to distribution network operators. Preliminary network measurements showed that the current THD on EBRI's feeder 2 varies between 24-28%. Notwithstanding, using the Current Total Rated Distortion indices (I_{TRD}) as recommended in IEEE 1547 [9] and in ref [10], we obtain I_{TRD} as 2.93% for G2V and 3.11% for V2G scenarios, where the rated current (I_{rated}) of EBRI's network is 1333A. Operating at 66% of I_{rated} (880A), we obtain I_{TRD} as 4.43% for G2V and 4.70% for V2G scenarios. Based on the resulting current TRD, EBRI's network current harmonics complies with IEEE 1547 and IEEE 519.

Table 6: Results of voltage harmonics, EBRI (practical)

	G2V	V2G	IEEE 519: 2014	ENA G5/4 (10MVA fault level)	IEC 61000-3-12
V_{rms} (V)	244	245	n/a	n/a	n/a
V_{HD5} (%)	2.2	2.2	5.0	4.0	n/a
V_{HD7} (%)	0.9	0.7	5.0	4.0	n/a
V_{HD11} (%)	0.2	0.2	5.0	3.0	n/a
V_{HD29} (%)	0.2	0.2	5.0	0.2	n/a
V_{HD31} (%)	0.1	0.2	5.0	0.2	n/a
V_{THD} (%)	2.5	2.5	8.0	5.0	n/a

Table 6 validates the simulated result as it shows that operating an EVSE in V2G mode has the same effect on voltage harmonics as operating the EVSE in G2V mode. Notwithstanding, no major increase was noticed in the voltage RMS value, this may be due to the presence of voltage regulating equipment on the network.

SITE 2: Car Park 12 Network Trial Results

Harmonic meter installation is yet to be completed at Car Park 12 and as such, we were unable to present live results.

DISCUSSION ON HARMONIC SUPPRESSION

In V2G operation, an EVSE will be exporting power from the EV battery to the distribution network. During this period, current (from the EV through the EVSE) along with the current's harmonic content is injected into the distribution network. Considering this, it would be reasonable to alter the EVSE harmonic content so that it cancels out individual current harmonic at the point-of-common-connection (PCC) to the distribution network.
This would entail changing the EVSE control scheme or converter components which currently is unfeasible, unless performed by the OEM during the EVSE manufacturing stage.

Potential Solutions

One solution may be for OEMs to design V2G EVSEs with open/flexible control functions that can be adjusted by Users to suppress harmonics under bad power quality scenarios.

Another option that is easier and flexible would be to connect a dedicated active power filter (APF) [11] to the PCC between the EVSE and the distribution network. This solution can be further simplified where more than one co-located V2G EVSEs are connected via a single point to the distribution network.

Both trial sites in this study have more than one co-located EVSEs, hence our proposed strategy would be to use only one APF just before the PCC to mitigate the harmonics associated with the EVSEs.

However, the challenge here becomes how best to size the APF and design the operational requirement to ensure it suppresses the harmonics without causing any problem further down the distribution network [12].

Sizing the APF should be based on the total rms harmonic current content of the group of EVSEs. To ensure accuracy the PCC to the network should be monitored during both V2G and G2V operation (normal charging) to get the actual harmonic current content. The APF should then be sized using the scenario with the higher rms harmonic current content.

CONCLUSION

This paper has evaluated the impact of V2G in suppressing harmonics and improving power quality on distribution networks using harmonic results from both simulated and practical V2G EVSEs connected to distribution networks.
The study found that operating EVSEs in V2G mode appear to worsen harmonic current content at the PCC to the distribution network but had little or no effect on the voltage harmonics. However, V2G operation of the EVSE did improve the voltage rms value at the PCC to the distribution network to be close/within statutory limits.
Based on the results, the paper recommends using active power filters to suppress harmonic current content at the PCC in situations where a V2G EVSE control scheme / converter component cannot be modified to operate in a similar fashion as an active harmonic filter.

Acknowledgments

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