IMPACT OF LV CONNECTED LOW CARBON TECHNOLOGIES ON HARMONIC POWER QUALITY

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ABSTRACT

The low carbon technologies such as heat pumps (HP), electric vehicles (EV) and photo-voltaic (PV) panels are challenging the established methods by which distribution systems are designed and managed. Whilst a reasonable body of literature exists in relation to their effect on energy demand and carbon emissions, their effect on harmonic power flow and voltage distortion is less well understood. This paper describes the results from field trials of heat pumps and electric vehicles as loads and, to compare, a laboratory study of PV as an example of a low carbon source.

INTRODUCTION

Government policy is promoting the connection of micro-generation such as photovoltaic (PV) solar cells to the distribution network [1]. At the same time, policy is also promoting new loads such as electric vehicles (EV) and heat pumps (HP) [2], seen as possible technologies to reduce carbon emissions and the reliance on fossil fuels [3]. All work presented in this paper is discussed in the report [4].

These technologies will affect the electrical demand profile at the national level [5], but less is known about their potential impact on the quality of supply on the local low voltage network. The concern is that if large numbers of devices which are EN 61000-3 compliant but which draw significant harmonic current are present on a feeder, the combined effect could lead to harmonic voltage distortion that could exceed the planning standard G5/4-1. Low-order harmonics are of particular concern because of their tendency to be synchronised between sources.

The presence of harmonic current in the feeder will result in i^2R current losses where the higher the harmonic current the greater the losses. In transformers the copper losses and the iron losses are increased [6]. This is especially important for harmonic currents that are in phase across the three phases. The zero sequence harmonic currents will sum in the neutral and cause a neutral voltage drop. This could further distort the voltage and cause extra heating. Work in [7] explores the i^2R losses under non sinusoidal conditions in cables and transformers. A mathematical model was developed that calculated the effect of harmonic distortion.

The impact of heat pumps on the LV distribution network was investigated in [8-10]. All three of the studies on heat pumps concluded that the existing distribution network was able to accommodate a small number of heat-pumps before voltage limits at the fundamental frequency were breached. None of the studies investigated the harmonic spectrum or the impact of the heat pump on power quality other than the magnitude of voltage.

Work in [11] investigated the contribution of harmonic distortion of current and voltage waveforms from PV. The PV plant did not cause any limit violations and the increase in magnitude of harmonic currents due to the operation of the PV plant was negligible.

HEAT PUMP TRIALS

The Energy Saving Trust (EST) and Passiv Systems provided measurement data of individual heat pumps across the UK at 10 sites each. Both ran their trials between the end of January 2014 and the beginning of March 2014. At the end of the trial, EST collected electrical data at 10 sites and Passiv Systems collected electrical data at 8 sites (2 sites did not yield electrical data).

Harmonic Current

The mean (averaged over time) and the maximum recorded in the trial of harmonic current for the 3rd, 5th, 7th, 9th, 11th and 13th harmonics were plotted in Figure 1 for all available heat pumps. Each maximum harmonic is presented by a different colour of bar. Each mean is represented as a white bar within the bar that represents that harmonics maximum value. For the Passiv data (HP 1 to HP 10), the power analysers recoded a maximum, mean and minimum for each measurement. The maximum harmonic current is the maximum of the maximum. The EST (HP 11 to HP 20) power analysers only recorded the mean and the maximum is the maximum of the mean.

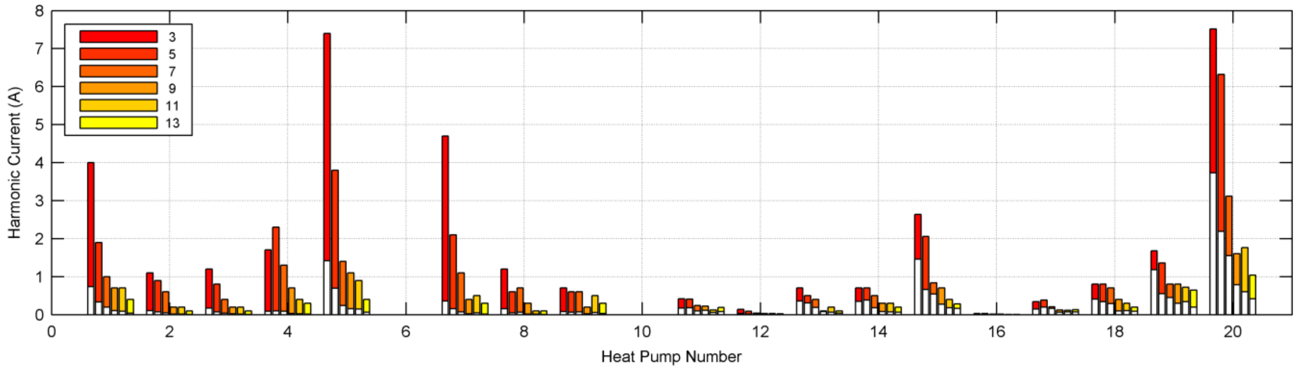

Figure 1: Maximum 3rd to 13th odd harmonic current measured from heat pumps. The mean harmonic current is shown as the white bar within the bar showing the maximum. HP 1 to HP 10 are from the Passiv trial and HP 11 to HP 20 are from the EST trial. Sites 6 and 10 did not yield any electrical data.

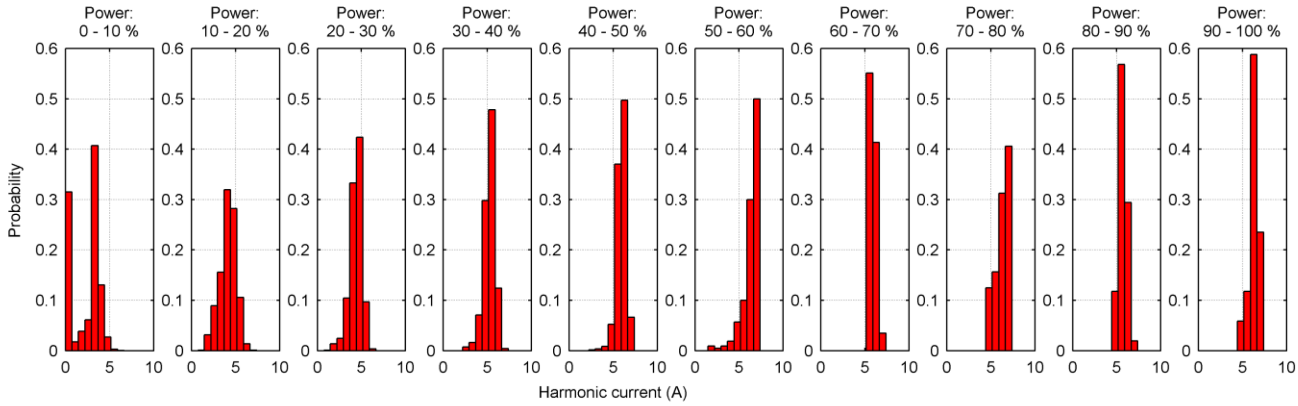

Figure 2: Probability of certain amplitudes of 3rd harmonics for power consumption of heat pump 5 in 10% bands (100% is 13.8 kW).

It is clear that the different brands of heat pump are quite different in terms of the harmonic current distortion they create. Most of the heat pumps draw harmonics which are well within EN 61000 limits. Two, HP 5 and HP 20, are within the product standard but have a rather high third harmonic of 1.4 A and 2.3 A respectively. In general, the 3rd and 5th harmonics were the two highest harmonics and the ones needing closest attention in determining network voltage harmonic limits. For the majority of the heat pumps the magnitude of the harmonic current decreases with harmonic number.

The difference between the maximum recorded value and the average is marked. The 3rd harmonic peak current for the four highest cases were 7.5A, 6.3A, 4.8A and 4A. The third harmonic is of concern because looking across all distorting loads, it tends to be drawn at the same phase relationship to the fundamental and therefore the 3rd harmonic contributions of all loads sum together. Higher harmonic orders are less and less likely to be phase aligned between different loads and so to some extent combine destructively [12]. Further, the third harmonic generated in this fashion will be a zero-sequence set that will flow in the neutral path causing additional voltage drops and heating. However, the angle of the harmonic current is not measured by the power analysers and thus any conclusions about the summations of harmonics in a feeder from a cluster of heat pumps are speculative.

A question that arises is, how often does the maximum harmonic current occur? For this a graphs is plotted in Figure 2 that explores the probability density function of the 3rd harmonic of HP 5 across a range of loading conditions. Heat pump 5 was chosen for this illustration because it has the highest peak harmonic magnitudes.

Figure 2 reveals several features of the 3rd harmonic distortion created by heat pump 5. First, at a constant power (any one of the sub-plots) there is still a range of possible amplitudes of 3rd harmonic current that will be observed. Second, as the power consumption is increased, the higher amplitudes of 3rd harmonic become more likely with the most likely amplitude changing from below 5 A for low power to over 5 A for high power. For context, it should be noted that at 100% power, heat pump 5 draws 59.9 A of fundamental frequency current.

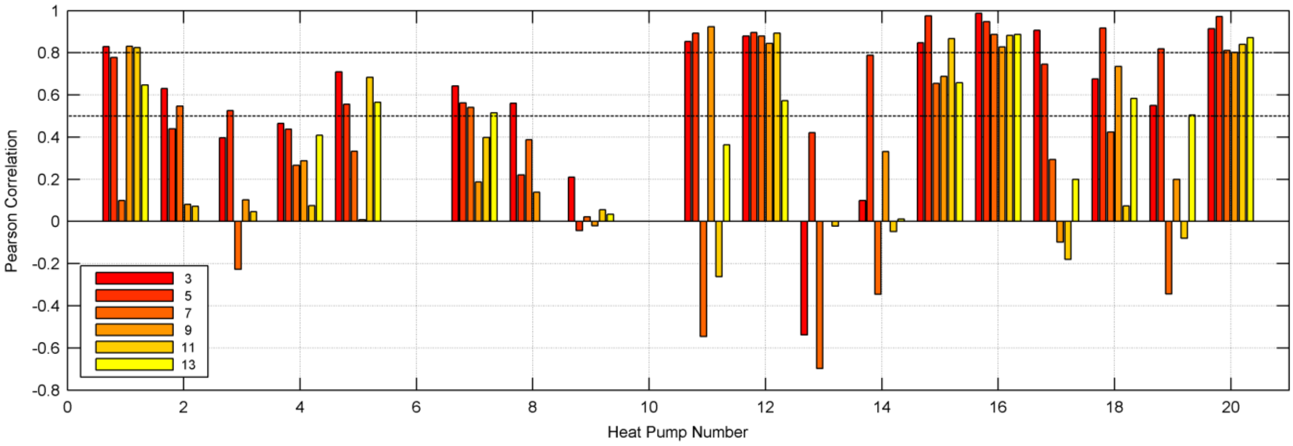

Figure 3: Correlation between harmonic current and heat pump power for all heat pumps.

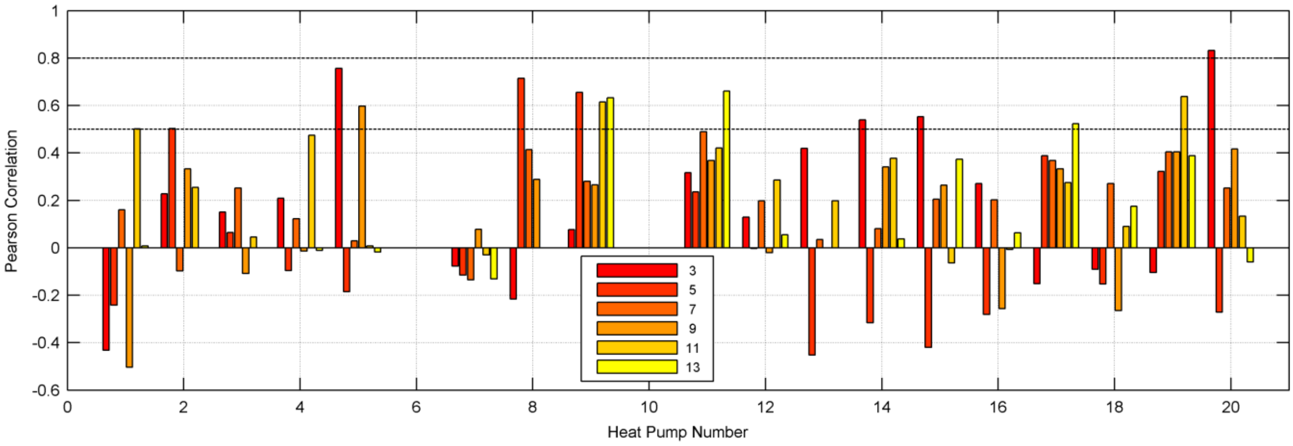

Figure 4: Correlation between harmonic current and harmonic voltage for all heat pumps.

It is important to note that heat pump 5 creates considerable 3rd harmonic distortion even when operating in the 0 – 10% of power consumption, which was not the case for all heat pumps. Heat pumps like HP5 will raise the THD of the network voltage at all times of day and is a "background voltage" of harmonic distortion.

Figure 3 shows the correlation (Pearson's Coefficient) [13] between the harmonic current magnitude and the heat pump power consumption. It can be seen that for some of the heat pumps (for example heat pumps 1, 11, 12, 16, and 20), there is a strong correlation between the output power and the harmonic current but for other heat pumps (for example 3, 4, 9, 17 and 19) there is not. In the cases with a high correlation, when the heat pump drew more current from the network, the heat pump would also present more harmonic emission to the network. For a low correlation case, the measured harmonic current did not coincide with the power consumed by the heat pump. A low correlation and high correlation are considered when the Pearson Correlation is less than 0.5 and greater than 0.8. Therefore from measuring individual heap pumps it is not possible to predict the harmonic current if the demand profile is known or calculated.

Harmonic Voltage

It is expected that as the load of the heat-pump increases, there will be a greater voltage drop along the cable from heat pump to the distribution board in the house, through the service cable to the feeder and along the feeder to the substation (and indeed beyond), thus there should be some correlation between the harmonic voltage and current. However, a great deal of the impedance listed above is common to other current paths and subject to uncorrelated harmonic voltage drops. Further data for the cable lengths and cable properties were not available.
Figure 4 shows the correlation between the harmonic current and the harmonic voltage (harmonic order by harmonic order) for each heat pump. Again, different colour bars are used for each harmonic.

Over half of the heat pumps have a low correlation between the harmonic voltage and harmonic current. Thus an increase in harmonic current from the heat pump did not cause an increase in the measured harmonic voltage. This implies that the heat pump was having a weak effect on the local voltage distortion perhaps because that distortion was largely due to other distorting loads in the neighbourhood. Some of the heat pumps have caused an effect on the harmonic voltage. As seen by the heat pump having a high positive correlation between harmonic current and harmonic voltage. As the harmonic current increase so the harmonic voltage also increased. This shows that heat pumps have the potential to distort the voltage of a feeder. Without information of the cable impedance that the heat pump is connected to and the other distorting loads in the neighbourhood, further analysis is not possible.

ELECTRIC VEHICLES

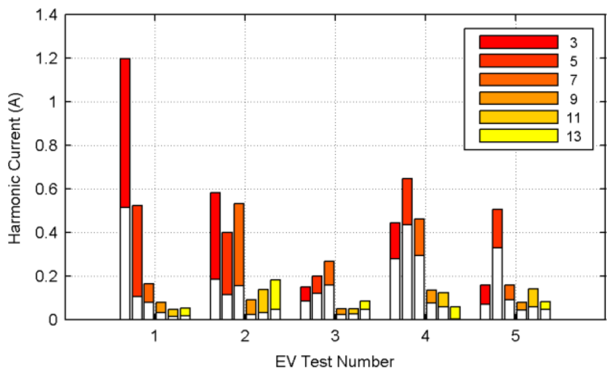

Figure 5: Maximum 3rd to 13th odd harmonic current measured from the EV charging events. The mean harmonic current is shown as the white bar within the bar showing the maximum.

The harmonic current from the charging of two EVs was recorded using a power analyser. The two EVs that were tested were a Nissian Leaf and a Peugeot iOn. A number of charging events were recorded.

Figure 5 shows the maximum and mean harmonic current from the charging of the EVs for harmonics up to the 13th. The figure shows large low-order harmonic currents with magnitudes that decrease with harmonic order. This is characteristic of a diode rectifier rather than an active rectifier with wave-shaping. The maximum third harmonic current observed was 1.2 A.

PHOTOVOLTAIC LABORATORY STUDY

This paper has considered two loads that are low carbon technologies. For a comparison to the low carbon loads, a low carbon source was considered. The laboratory test of four PV inverters was set-up as shown in Figure 31 and consisted of: the PV inverters selected were considered typical of a domestic installation. The equipment used was:

1. A 10 kW power supply,
2. A power measurement unit,
3. An isolation transformer and,
4. The PV inverter under test.

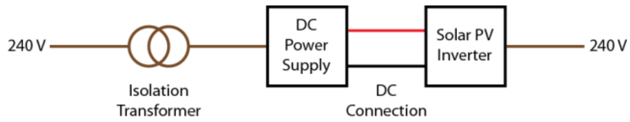

Figure 6: Diagram showing the experimental setup for the PV laboratory study.

Harmonic Current

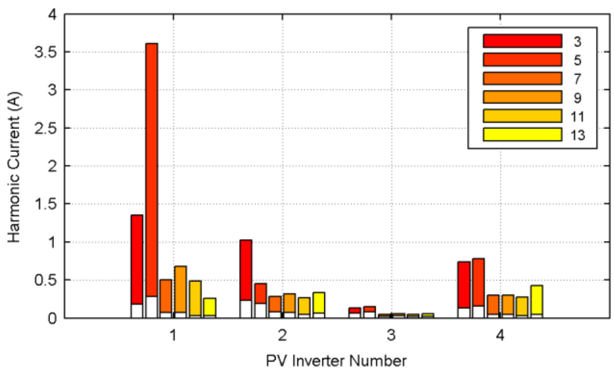

Figure 7: Maximum 3rd to 13th odd harmonic current measured from solar PV inverters. The mean harmonic current is shown as the white bar within the bar showing the maximum.

The mean and maximum harmonic current from each of the four solar PV inverters is plotted in Figure 7. The first observation is that the mean harmonic demand from the four inverters tests in the laboratory is much lower than the harmonic current generally observed from the heat pumps. This excludes the 5^{th} harmonic from the first inverter. The fifth harmonic is the largest magnitude harmonic current produced by three of the four the inverters. It is noted that the general supply voltage in the laboratory has a significant 5th harmonic voltage even when no-load is connected which is considered to be due to the large 5th harmonic current drawn by the ICT equipment elsewhere in the building. It is possible that the inverters are influenced by the existing 5th harmonic voltage to produce some 5th harmonic current but that is not certain.

CONCLUSIONS

The heat pumps and EV charger that were examined exported a large amount of 3rd, 5th and 7th harmonic current. There was a base line of harmonic current that slightly increased as the demand from the heat pump and EV increased. This will present a constant harmonic current to the distribution network. The heat pumps that were recorded showed a wide range of harmonic measurements. This could be related to the design of the heat pump or the usage and installation environment of the heat pump since the harmonic distortion varied with load. For comparison, PV inverters tested within the laboratory emitted a much lower harmonic current than the heat pumps and EVs. The PV inverters exported largely sinusoidal current where the maximum harmonic recorded after removing an anomalous result was less than half an amp.

The heat pumps and EVs drew a significant amount of low order harmonic current. Low order harmonic are typically phase aligned and will sum within the feeder. The phase of the higher order harmonics tends to be randomly distributed and thus will cancel within the feeder. Because the low-order harmonics tend to be drawn at similar phase angles since the distortion is synchronised to the mains cycle (most especially for identical equipment) there is a danger that, even if each item is compliant with a product standard such as EN 61000-3, the accumulated low-order harmonic currents in the network would give harmonic voltages exceeding the planning standard. High power equipment with large amplitude harmonic currents would be the prime concern.

It is clear that there is not a single answer to the question of whether these technologies will cause power quality problems on LV feeders. Even among the relatively small number of cases examined, there are big differences in levels of harmonic current. The PV inverters were found to have low distortion, comparable with the best of the heat pumps and with a low likelihood of enough harmonic current flowing to on a feeder to cause a problematic level of voltage distortion. However, the worst performing heat pumps and the one example EV charger do appear likely to cause problems when deployed in clusters, although there may well be other constraints which are met before the harmonic voltage constraint. If all of the devices rightly claim compliance with EN 61000-3 it will be difficult to assess a mixed deployment without detailed knowledge of the equipment concerned or use of a conservative worse-case assessment.

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