On-board electric vehicle charger noise assessment and overview of power electronic noise sources

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Improvements in the energy density and efficiency of power electronics have brought these components closer and closer to our daily lives. In the transport sector, the improvements of power electronics can be translated into the capability of supporting larger currents, increasing thus the risk of audible noise and vibration related problems. The importance of the harmonic distortion to the audible noise generation is highlighted and the mechanism of audible noise generated in passive components such as capacitors and inductors is reviewed. The analysis of the audible noise generated by an on-board electrical vehicle charger is presented. The possible impacts and solutions to the environmental noise are assessed in a context of high penetration of electrical and plugging-in hybrid vehicles as well as vehicle-to-grid schemes.

1 Introduction

Power electronic have been employed in power control application since late 50's with the introduction of commercial grade thyristor, followed by an extensive development in the sector from 1975-1995 with the introduction of metal-oxide semiconductor filed-effect transistor (MOSFET), gate turn-off thyristor (GTO) and insulated gate bipolar transistor (IGBT) [1]. The constant development of semiconductors technology allowed the reduction in volume, mass and cost of power electronic converters – making them a indisputably part of the electrification of the transport sector.

Despite their relative high performance and the quality of the rectification, power electronic converters generate electrical harmonics during their operation. Harmonics caused by the switching converters can lead to audible noise in power electronic components, as electromagnetic forces generated by these harmonics in passive components such as inductors, capacitors, transformers and bus-bars can lead to vibration and airborne noise emission. The aim of this paper is to present a brief conceptual review of electromagnetic audible noise in power converter equipment including an example of audible noise analysis during charging of on-board vehicle. As an ultimate goal, the combination of a conceptual review with a practical analysis in the field aims to advert to the importance and relevance of the subject in the actual context of high penetration of BEV and PHEV vehicles and the possible impacts to environmental noise.

2 On-board AC fast charger

Battery electrical vehicles (BEV) and plugin-in hybrid vehicles (PHEV) can be charged by plug-in the vehicle to the AC-mains.

Since energy is stored in electrochemical batteries, the AC power from the grid has to be rectified to DC to be latter used in the AC form in a (typically) synchronous motor. In addition to the AC/DC & DC/AC conversion, power quality issues optimisation of the charging times and operation of the vehicle requires other on-board systems such as filters, and DC-DC converters. The power electronic converters can be classified in 4 main categories: AC-DC rectifiers, DC-AC inverters, AC-AC and DC-DC converters.

A schematic view of an on-board EV charge is shown below. Unlike early single-phase chargers, the 3-phase chargers became available in 2013, allowing faster charging at power ratings of 22 kW up to 43 kW. The basic components of the on-board charger may include the input and power factor filters – responsible for the limitation of harmonics introduction in the grid and transformer for galvanic insulation – followed by a AC/DC rectifier that delivers DC current to vehicle's battery.

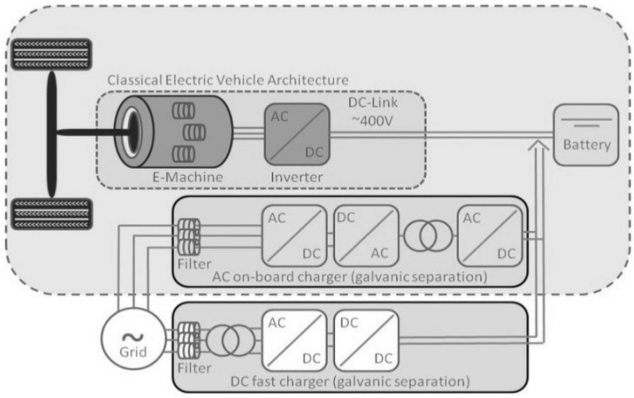

Figure 1: Schematic view of on-board charger and electric vehicle architecture (extracted from [2]).

During driving mode, the AC power required to drive the E-motor is obtained by an AC/DC inverter. It can be noticed as well in the figure above that DC chargers may coexist with on-board charger, that is, allowing fast direct-current charging with off-board borne (e.g. CHAdeMO) where AC/DC rectification in performed in the stationary borne.

Several different topologies can be employed in the on-board power electronic to perform DC/AC rectification [3], [4]. Since a thorough review of the subject is beyond of the scope of this paper, it should be noted that the state of the art converters is based on bidirectional voltage source converters controlled by a switching based strategy such as pulse width modulation (PWM). The importance of the bi-directionality is that the power can flow in both ways, i.e. allowing the electrical motor to recover vehicle's kinetic energy, as well as opening possibilities to vehicle to grid (V2G) schemes where a BEV or PHEV can serve as temporally energy storage to the grid.

2.1 PWM converters

As previously described, during the charging cycle, single or three-phase AC is rectified to DC current, the operation of PWM converter can be in short terms described as controlled switching between different conduction states, the states are determinate by comparing a reference signal r(t) to a carrier wave c(t), as depicted below. The carrier wave is normally triangular while the reference signal is the desired output signal.

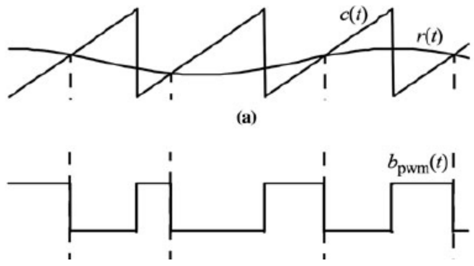

Figure 2: Pulse width modulation of constant frequency trailing edge saw tooth carrier (extracted from[5]).

As one can anticipate, the rectified signal will contain harmonic distortion. Detailed calculation of the harmonic spectral of PWM converters based on double Fourier series method can be found in the literature [5], [6]. A current spectrum obtained during the charging at roughly 21 kW is depicted below - current is measured at the rectifier output.

The major harmonic component is at the frequency of the PWM switching along with the side bands, as per the relation below, where the f_c and f_1 are the carrier frequency (10 kHz) and the AC grid fundamental (50 Hz) respectively.

$$f = mf_c + nf_1 \quad (1)$$

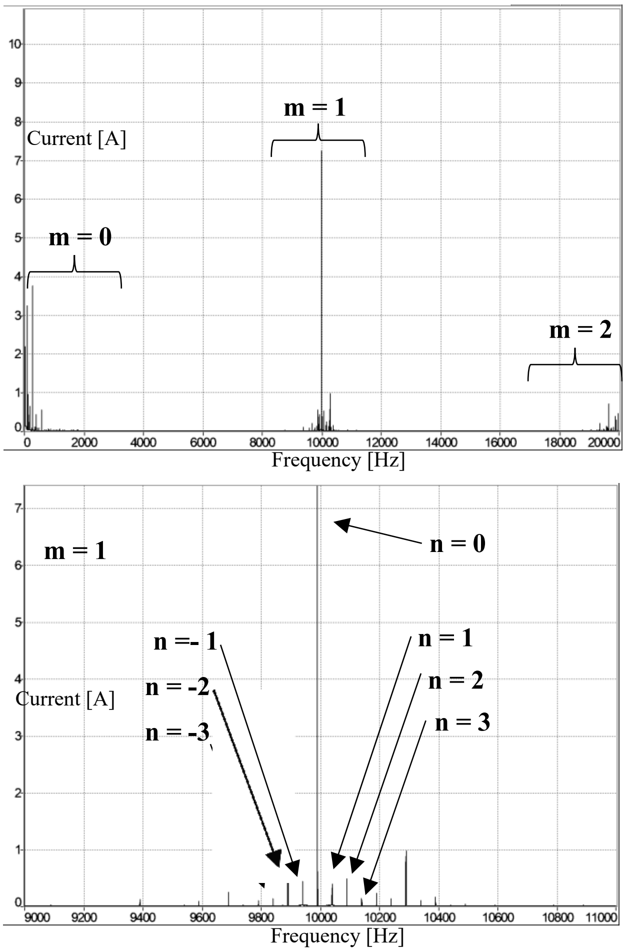

Figure 3: Example of the DC-side current spectrum of a 22 kW charger up to 20 kHz and zoomed around the carrier wave frequency 10 kHz. The harmonic currents are concentrated around m = 0, 1 and 2.

Despite being inherent to the operation of power electronic converters, the amplitude as well as the frequencies of the harmonics can be either reduced or shifted in order to control audible noise levels. It will be seen in the next section that the electric and/or magnetic forces arising from the high frequencies harmonics are of primary importance in controlling the audible noise emission.

2.2 Harmonic forces

In addition to the active components (e.g. IGBT's); the on-board chargers rely on the passive components for current and voltage stabilisation, filtering and impedance matching, these components are grouped together in what is normally called power electronic controller (PEC). The main passive components responsible susceptible to audible noise generation are:

- Inductors
- Power capacitors
- Transformers
- Cables and busbars

The audible noise from inductors and transformers is well known to be related to magnetic forces arising in the winding and in the core (when present). The amplitude of the magnetic forces in the windings of an inductor or transformer is proportional to the current density and the magnetic flux density, which in turns is directly proportional to the element current, thus the magnetic force can be expressed in terms of the square of the current loads [7]:

$$F_m \propto I^2 \quad (2)$$

It can be shown that if current time signal is decomposed into its harmonic components and introduced into equation (2), after some trigonometric manipulation it can be shown that magnetic forces due to harmonic currents at frequencies ω_i and ω_j with amplitudes I_i and I_j respectively are:

Table 1: Magnetic force frequencies and amplitude.

Magnetic force frequency	Amplitude
$\omega_i + \omega_j$	$\propto I_i I_j$
$\omega_i - \omega_j$	$\propto I_i I_j$
$2\omega_i$	$\propto \frac{I_i^2}{2}$
$2\omega_j$	$\propto \frac{I_j^2}{2}$
0	$\propto \frac{I_i^2 + I_j^2}{2}$

The direct implications of the quadratic dependence of the magnetic forces with respect to the currents is that up to n² harmonic forces can act on the inductor or transformer winding with n harmonic currents are present. In addition, and perhaps most importantly the force amplitude of a given force harmonic is proportional to the product of the harmonic currents amplitude, therefore even low amplitudes of high frequency harmonics combined with a high amplitude of fundamental or DC current can lead to significant force levels in the high frequency range.

Magnetostriction can be responsible to an important part transformers. To some extent, all ferromagnetic materials are susceptible to suffer strains under the action of an external magnetic field [8]. The equivalent forces on the core, responsible for the strain, have the same frequencies as the magnetic forces described above, thus it is not trivial to differentiate the audible noise contribution from magnetic and magnestostriction origin.

The forces arising in conductors can be sometimes overlooked when analysing the possible noise sources in charger or power electronic controllers. Since electrical conductors may carry high density currents and they are usually placed at relative close distances, the amplitude of magnetic forces (Lorentz forces) may be non-negligible. In addition, it is usual to employ thin flat conductors (busbars) for improving heat dissipation and avoiding skin effects, which can make the busbars more susceptible to vibration and audible noise emission.

So far, the importance of the magnetic forces in inductors, transformers and conductors has been pointed out – in addition to the magnetically-induced forces, electrostatic attraction of capacitor electrodes is generated when a voltage difference V is applied to the capacitor.

A typical capacitor design can be described as an aluminium vapor-deposited on a thin dielectric film such as polypropylene (a few microns thick) forming the electrodes and dielectric *sandwich*. Since several micro-Farads or even mili-Farads can be required, a typical capacitor may be constituted of many squared meters of dielectric and aluminium electrodes wound to form a single capacitor.

The electrostatic forces (also known as electrostriction) compressing the dielectric material are dependent to the quadratic value of the voltage difference across the plates, therefore the same type of harmonic forces described in eq. (2) and table 1 are expected in the case of the capacitors [9].

In summary, pulse-width-modulation is responsible for generating harmonic distortion in the converter currents. The main harmonics are at the multiples of the carrier's wave frequency along with the side-bands at multiples of the reference signal. Finally, forces in the passive components can be found at a wider spectrum range due to the quadratic dependence to the currents or voltages to each they are submitted. As one can immediately expect, these forces can cause the structure of the components to vibrate and to radiate audible noise. In the next section, possible methods to control the audible noise generated by on-board chargers and power converters in general will be discussed.

3. Audible noise control

The control of audible noise of on-board chargers, as well as other controllers doted of power converters driven by PWM can be divided into three main categories: (a) reduction of the ripples and harmonic distortion in the current or voltage spectrum thus causing a positive impact in the reduction of the harmonic forces, that main include the shift of the harmonic frequencies to less critical or even non-audible range, alternatively one can (b) employ classical noise and vibration control such as enclosing, decoupling, damping in order to reduce the acoustical emission in the range of interest and (c) work in the design and materials of the passive components in order to obtain a reduction in acoustic levels.

Since most of the audible noise and annoyance during the charging of an BEV or PHEV can be associated to the frequency of the PWM carrier wave, one initial work around the audible noise problem would be to shift the PWM carrier frequency above the audible noise range, that is above the theoretical 20 kHz threshold. In fact, this method is implemented with success in household appliance which regularly operate with DC currents, such as laptop charges. Power converters controlled by PWM at such high frequencies would generate most of its audible noise above the threshold of human hearing, thus reducing the risk of noise annoyance.

The problem with very high frequency PWM carrier (i.e. above 20 kHz) is that what is known as "switching losses" will inevitably increase.

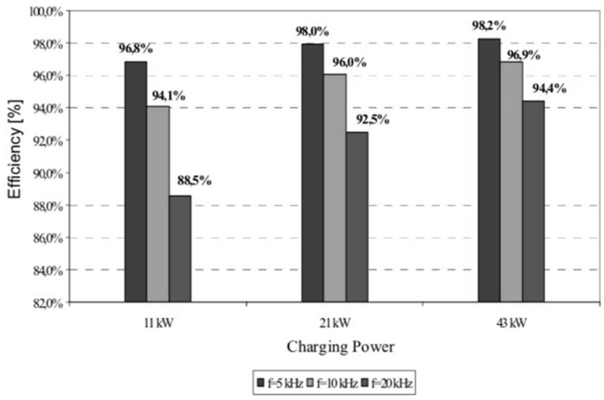

Figure 4: Calculated efficiency of on-board constant switching frequency charger (extracted from [10]).

In the figure above, the efficiency of the power electronic inverter calculated based on a model of fixed switching frequency converters at 5 kHz, 10 kHz and 20 kHz are presented for 3 charger power ratings (11 kW, 21 kW and 43 kHz). Clearly there is a trade-off between the efficiency and the power quality obtained at higher switching frequencies, that is, in order to reduce the quantity of harmonics or to generate harmonics above the human audible range the converter will be inevitably less efficient [10].

It has been discussed so far, the use of single frequency PWM carriers. Variable frequency PWM strategies can be used not primarily to reduce the overall harmonic distortion of a power converter but to reduce the contribution of single frequencies. In result, the annoyance level of audible noise generated can be greatly reduced. Several random pulse width modulation strategies have been tested showing significant reduction in single harmonics, below a comparison of single frequency PWM (SVPWM) with continuous and discrete random PWM (RPWM) [11]:

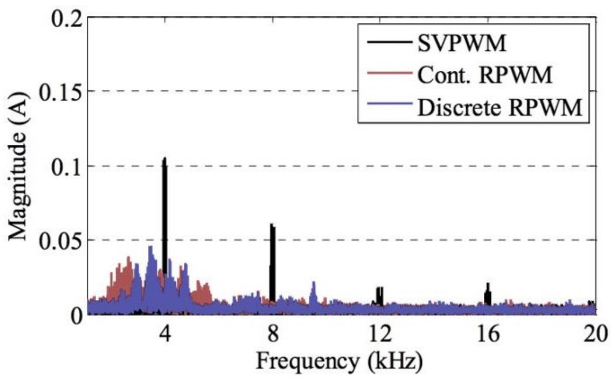

Figure 5: Comparison of current spectrum of single frequency PWM (SVPWM) and random PWM (RPWM) – extracted from [12].

Several publications on the design of PWM spectrum for reducing audible noise in inverter driven motor are available, the same methods can benefit on-board charger noise and other power controller equipment [13].

The means reduction of the harmonic distortion in a converter is not limited to the PWM controller, reduction in the current ripples in an inverter – such as the one used in the on-board chargers – can also be achieved by using an output filter of an inductor in series with the load and a capacitor in parallel to the load. The amplitude of the ripples and consequently the harmonics will be reduced once the ratio of the inductor L to the capacitance C (L/C) is increased [14]. Normally the losses, heat dissipation and size and cost of the components will limit the ratio L/C.

The sensibility of the passive components to the harmonic forces plays an important role in determining the audible noise emission. Since the electrostatic or magnetic forces can be found in a wide range of frequencies, alternative material and constructions can be employed, such as the use of low-noise non-oriented steel as electrical steel in inductors and transformers. Alternatively, air core inductors can be employed eliminating the magnetostriction contribution to audible noise – but limiting the inductance values due to relatively low air permeability when compared to electric steels [15].

Finally, the audible noise can be reduced by mean of the usual solutions employed in automotive industry such as using high acoustic absorption material, decoupling components and reducing the structure-borne noise, reduce the vibration levels using damping materials.

In summary, the discussed means of reducing the audible noise of the on-board charger were:

- Use of PWM carrier frequencies above the human hearing limit,
- Employing random PWM control in order to reduce the annoyance generated by single frequencies,
- Reduce the amplitude of the ripples in the inverter by mean of an output filter, employing large values of L/C,
- Use of low-noise iron cores or air-core inductors to reduce or eliminate magnetostriction,
- Reduce individual component audible noise emission by proper design, avoiding resonances in the frequency range of harmonic forces generated by power converters,
- Use of classical noise control techniques to enclosure and baffle airborne noise and damp structure-borne noise.

4. Environmental Impacts

Although the participation of electric vehicles (BEV and PHEV) have experienced enormous continuous growth in recent years (stock growth of 59% in 2016), the world electrical vehicle stock has just passed 2 million in 2016, nevertheless it just account for roughly 0.2% of the worlds fleet [16]. It means that most of the benefits, as well as the consequences of the intense penetration of electrical vehicles has not yet been seen.

The reduction of the noise during the driving condition is well known and it is advertised as one of the benefits of the electrical vehicles, this is true for the vehicle's occupants but as well as, in a lesser extent, to the urban environment. Noise level in urban centres are expected to reduce when most of the internal combustion engine (IEC) vehicles have disappeared, even when considering the use of ADAS [17]. Further reduction is expected if non-ICE heavy trucks and light duty vehicles would be considered. Despite all benefits of noise reduction of the electric vehicle during driving mode, the impacts of the noise caused by the charging of BEV and PHEV have received little attention so far.

An audible noise spectrum in measured at 1 m of a commercial vehicle during fast AC charging (> 20 kW) is shown below. It is remarkable the emergence of high frequency noise associated with the PWM generated harmonics, in this case the 1/3 octave band of 10 kHz and 20 kHz. Although having relatively low levels, the annoyance generated by the 10 kHz pure tones and its side band is quite disturbing.

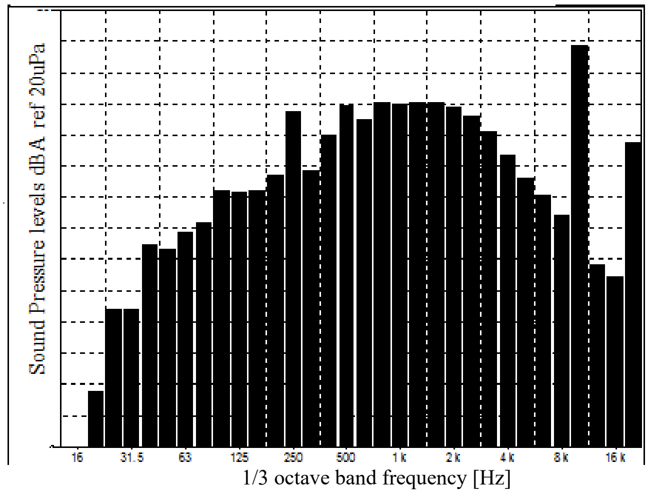

Figure 6: Sound pressure levels at 1m during >20 kW charging of commercial BEV.

Advancements in the concept of smart-grids and V2G schemes, where each vehicle could be used as a temporary energy storage to the grid, could allow vehicles to be charged and discharged multiple times while parked and not in used, e.g., charging during the night when the grid is not under load-pressure and then *selling* its energy back to the grid during peak loads.

Such advancements in the electrical vehicles and V2G could create the need to include charging vehicle in the road traffic prediction and noise planning of cities. Correct planning and measures could prevent, for example that parking lots sounded more like high voltage substation full of annoying high frequencies pure tones.

Although the current stock of electric vehicle (BEV and PHEC) is very timid, intense political pressure and negative public opinion towards the IEC vehicles will make the transition to electric vehicle faster in large cities, where the need for a proper assessment of the environmental noise impact is even greater – regulation will be an important step in achieving environmental goals, such as setting maximum allowed noise levels during charges or limiting the instantaneous charging power in order to restrict the noise levels.

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