Characterization of the Emission of an Electric Bus Inductive Charging in the 2 kHz to 150 kHz Range

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Abstract—The foreseen increasing penetration of the Electric Vehicle is causing concern about its impact on power quality, especially with respect to distortions in the frequency range from 2 kHz to 150 kHz, also known as supraharmonics. This relatively new power quality issue is recently getting more attention from the research community and the standard setting organizations. The main reason is the increasing presence in the grid of power electronics devices with switching frequencies of tens of kHz. Electric Vehicle chargers are among them and, therefore, their impact on supraharmonic distortion needs to be accurately characterized and modeled. This paper presents the characterization of an electric bus wireless charging, currently part of the EURAMET project MICEV. The aim of the work is to overcome the lack of knowledge on the supraharmonic emission due to the inductive charging of Electric Vehicles. The results of field measurements of an electric bus wireless charging are presented and a frequency analysis is performed according to IEC 61000-4-7 standard, studying the origin and the behavior of the supraharmonic spectral components.

Index Terms—Electric Vehicles, Inductive Charging, Power Quality, Power System Harmonics

I. INTRODUCTION

The Electric Vehicle (EV) represents an attractive alternative to the traditional internal combustion engine vehicle. Social, economic, and environmental factors are driving its increasing penetration in the grid [1]. Moreover, being equipped with energy storage devices i.e., batteries, EVs offer the additional possibility to provide ancillary services to the distribution grid and contribute to voltage and frequency control [2]. However, along with promising features, new challenges arise as well. Among them, concern is raising about the impact on distribution networks in terms of Power Quality (PQ). The effect of the EV integration on PQ parameters such as unbalance [3], [4],

harmonics [5]–[7], and voltage fluctuations [8], [9] have been largely investigated, as well as system losses and transformers lifetime degradation [10], [11].

Alongside with these traditional PQ issues, unintentional emission in the range of 2 kHz to 150 kHz—also known as supraharmonics—has recently attracted the attention of the research community. Whereas the harmonic emission in the frequency range below 2 kHz is well understood and regulated, current and voltage distortion in the range of 2 kHz to 150 kHz lacks of systematic knowledge and standardization. It is widely accepted that it can be expected to observe distortion in the grid with the same frequency as the commutation frequency of power electronics devices, but the propagation and interaction mechanisms of supraharmonic distortion are not well understood yet. It is also not clear whether it is reasonable to expect even more frequency components or not [12]. The full extent of the effects on power systems is still unclear, but it has been reported that supraharmonic distortion can cause additional heating in electronic devices, audible noise, malfunction of equipment, and wrong smart meter readings [13]. Its main causes that have been identified so far are Power Line Communication (PLC) and power electronic converters, whose switching frequencies lie in this frequency range.

Since EV chargers typically employ switched power electronics like active Power Factor Correction (aPFC) or Pulse-Width Modulated (PWM) controlled rectifiers, they produce emission in the frequency range from 2 kHz to 150 kHz. However, there are only few works in the literature that study the impact of EV on supraharmonic distortion. In [14] an EV is included in the study of the interaction between several supraharmonic emitting devices, showing the propagation behavior of the resulting distortion. In [15] a characterization of the supraharmonic emissions of six EVs in laboratory conditions is presented, showing that the emission due to the charger switching frequency depends on the charging topology and the charging state. Some guidance is also provided for modeling the emission. Reference [4] analyzes the evolution

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme, and from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 676042.

of the emission in the range from 2 kHz to 150 kHz during a controlled coordinate charging of up to nine EVs. Through the time-frequency analysis, the emission of the EVs is clearly identifiable. Although supraharmonic emission has usually very low amplitude, in [4] it is shown that it can become sufficiently high to produce a significant influence on PQ. Reference [6] analyzes the impact of charging infrastructures with a high number of EVs on supraharmonic emissions, together with other PQ indicators. The results of measurements taken at a central charging infrastructure are presented, showing the increase of emission from 2 kHz to 150 kHz inside the installation with increasing number of charging EVs.

There is agreement on the need of characterizing the high frequency emission of EV charging in different conditions, in order to be able to develop emission models. The modeling of sources, propagation, and effects of distortion in the frequency range from 2 kHz to 150 kHz is essential to ensure the correct operation of the grid and the devices connected to it. In this context, this paper studies the frequency emission in the range from 2 kHz to 150 kHz caused by EVs employing wireless charging. Wireless (or inductive) charging is a fast growing technology, with numerous private and public investments [16] but, to the best of the authors' knowledge, the supraharmonic emission due to wireless charging has not been studied in the literature yet and its characterization is beneficial towards the development of adequate emission models. Such models, in turn, are necessary to be able to estimate the impact of high numbers of EVs connected to the grid, especially since their penetration is expected to increase significantly in the next years. This work presents an overview of the results of a measurement campaign of emission of an electric bus during inductive charging, using a charging system developed by some of the authors. Section II provides a description of the charging platform and the measurement strategy employed in this work. Section III illustrates the results obtained from the background analysis and from the measurement of the charging platform under normal operating conditions, with a discussion on the Electromagnetic Compatibility (EMC). Finally, the conclusions are presented in Section IV.

II. MATERIALS AND METHODS

A. The Inductive Charging Platform

The inductive charging system, developed within the VIC-TORIA project by some of the authors [17], is currently part of

the EURAMET project MICEV [18] and its topology is shown in Fig. 1. The grid-side AC/DC inverter is made by a three-level Neutral Point Clamped (NPC) topology with Nearest Three Vector (NTV) modulation technique. A current ripple of 20.1 kHz is achieved with 6.7 kHz switching frequency. The buck converter is composed by three DC/DC interleaved buck converters, where each leg is switched at 25 kHz, resulting in a total switching frequency of 75 kHz. It is followed by a High Frequency (HF) converter, a dual active bridge converter switched at 27.8 kHz, that feeds the Inductive SP-S Power Transfer (IPT). On the secondary side, a diode-bridge connects directly to the EV battery for the charge. More details on the charging system can be found in [19]. Fig. 2 shows a picture of the electric bus during the measurement.

B. Measurement and Data Analysis

The measurements were taken at the Point of Common Connection (PCC), measuring both current and voltage on all the three phases. Time domain waveforms were acquired at 500 kS/s with a 16 bit resolution, using two NI PXIe-6124 modules (installed on a NI PXIe-1071 chassis), equipped with three Hameg HZ115 voltage probes (1500 V input voltage and 30 MHz bandwidth) and three Tektronix TRCP0600 current probes (peak current 600 A, bandwidth from 12 Hz to 30 MHz). The recorded waveforms were stored on a computer for the analysis, performed with a MATLAB based application.

There is currently no standardized method for the assessment of the supraharmonic distortion. The IEC 61000-4-7 and IEC 61000-4-30 standards suggest three possible methods for the analysis. Based on recommendations and studies found in the literature, it was decided to employ the method proposed in IEC 61000-4-7. It is a Fast Fourier Transform (FFT) performed on a 200 ms rectangular window, not synchronized with the fundamental frequency. The Fourier frequency components shall then be grouped into 200 Hz bands. The advantages of this method over the other two are the higher frequency resolution and a better suitability to grid measurements [20], [21]. Although not part of the method, in [22] it was shown that a High Pass Filter (HPF) is required to achieve good resolution and avoid energy leakage typical of Fourier analysis. For this reason the digital HPF proposed in [22] is employed to remove the energy content below 2 kHz before the analysis. In order to avoid the distortion due to the filter transients, all the waveforms were recorded for a total time of 300 ms. Each

Fig. 1. Schematics of the Metrology for Inductive Charging of Electric Vehicles (MICEV) wireless charger topology.

Fig. 2. Electric bus under assay.

recorded signal was filtered and then, the required 200 ms rectangular window was selected removing the filter transients.

III. RESULTS

This section presents the results of the measurements performed on the wireless charging platform. Firstly, the characterization of the electrical background in the vicinity of the charging platform is presented. Then the results of the measurements at the PCC of the charging platform during charging operation are analyzed and, finally, the EMC is discussed.

A. Background Analysis

In order to characterize the electrical environment in the range from 2 kHz to 150 kHz, a background measurement has been performed at the charging station. A 300 ms voltage signal has been acquired every minute for 17 hours during which the platform was not in use i.e., from 17:00 until 10:00 of the following morning, collecting a total of 1020 measurements. Each signal has been analyzed following the procedure described in Section II-B. The resulting 1020 spectra are shown in form of a spectrogram in Fig. 3, where it is possible to observe the time evolution of the background emission close to the charging platform, especially when no other devices are in use in the laboratory. Fig. 4, instead, shows the amplitude in time of three of the most intense emission frequencies in the spectra. The values are presented in the logarithmic unit $\text{dB}_{\mu\text{V}}$ ($\text{dB}_{\mu\text{A}}$ for current), which is defined using $1 \mu\text{V}$ as reference level ($1 \mu\text{A}$ for current). In this way $0 \text{ dB}_{\mu\text{V}}$ correspond to $1 \mu\text{V}$ ($1 \mu\text{A}$) and each decade is represented by 20 dB. The background emission has very low values, being always below $86 \text{ dB}_{\mu\text{V}}$ (0.02 V), except for the emission at 53.1 kHz, which gets as high as $100 \text{ dB}_{\mu\text{V}}$ (0.1 V). The emission at 53.1 kHz is most likely due to the lighting system of the building, based on fluorescent lamps, which are a known source of supraharmonics due to their electronic drivers [23]. It can be seen that emission level is $5 \text{ dB}_{\mu\text{V}}$ lower at night, when the laboratory is empty, and then it is higher again when people are in the laboratory and all the lights are

Fig. 3. Time-frequency analysis of the background emissions.

Fig. 4. Evolution of the emission level of the most intense spectral components of the background.

on. The emission at 39.9 kHz shows a change in behavior as well, from approximately 04:00 to 08:00, which can be seen in Fig. 3 too. The origin of this emission and of its change, however, could not be identified. The background levels are, in general quite low and do not represent a concern for the measurements.

B. Emission of the Wireless Charging Platform

Fig. 5 shows one cycle of the current and voltage waveforms measured at one phase of the PCC of the charging platform. This measurement is representative of the optimal operating conditions, as the coils were perfectly aligned and the charger was working at nominal power. All the three phases were measured but, since the results are similar for all phases, only one will be analyzed in the paper. The voltage waveform in Fig. 5 shows the typical flat-top distortion, commonly found in public low voltage networks and that can cause further harmonic emission from the device [24]. Fig. 6 shows the Fourier spectrum, obtained from the current measurement

Fig. 5. Current (top) and voltage (bottom) waveform at the PCC of the charging platform.

according to IEC 61000-4-7, as explained in Section II-B. Although the supraharmonic range is defined up to 150 kHz, the spectrum is shown up to 204 kHz in order to better show the emission patterns and identify its origin. A red dashed line marks the limit of the supraharmonic range. As described in Section II, the switching frequencies of the different power electronic converters are known. For convenience, they are repeated here:

- $f_{sw1} = 20.1 \text{ kHz}$ grid side AC/DC
- $f_{sw2} = 75.0 \text{ kHz}$ buck DC/DC
- $f_{sw3} = 27.8 \text{ kHz}$ high frequency DC/AC

Since manufacturers are usually reluctant to share construction details of their products, this information is normally not known for commercial devices and must be deduced from the spectral analysis, but this is not always possible, as in some cases of [15]. In this work, however, the exact a priori knowledge of the switching frequencies represents an additional advantage that helps in the analysis of the spectrum and allows a deeper understanding.

From the spectrum it is possible to identify the components produced by the grid side AC/DC converter, at 20.1 kHz (f_{sw1}), as one of the most intense emission. It is also possible to locate its second (40.2 kHz) and third harmonics (60.3 kHz). They can all be considered broadband emission, as they span across contiguous bands. They are identified in Fig. 6 by orange dots. Moreover, another structure can be identified, represented by eight narrowband spectral components and marked by yellow stars in Fig. 6. These spectral components are, together with f_{sw1} , the most intense ones in the spectrum and represent the greatest impact. They originate from the interaction between the single emissions of the several converters that belong to the wireless charger. The first peak of this group is located at 23.9 kHz, which is the arithmetic average of f_{sw1} and f_{sw3} :

$$\frac{(f_{sw1} + f_{sw3})}{2} = 23.95 \text{ kHz} \quad (1)$$

The second peak, then, is separated by the first one by exactly

$$f_{sw3} - f_{sw1} = 7.8 \text{ kHz} \quad (2)$$

This phenomenon resembles the beat effect, well known in acoustics and due to the interference from two different frequency components, resulting in additional frequencies i.e., the average and the difference of them. However, in this case the resulting effect is more complicated than just the interference of two components, as it can be seen by the remaining six peaks (still marked by yellow stars), which are obtained by rigidly shifting the first two peaks by exactly $2f_{sw3}$. A closer look reveals that the two-peaks structure can be found also with a shift of only $1f_{sw3}$ (for example at 51.7 kHz and 59.5 kHz), but much attenuated (these attenuated peaks are marked in Fig. 6 by yellow plus signs). A similar beat effect was already observed in EV supraharmonic emission analysis, but in a simpler form. In [6] the emission from two identical EVs connected to the same charging station was analyzed. In that case the switching frequencies were almost identical, but with a slight difference—only 0.5 Hz—causing a modulation with a period of 2 s, visible in time domain (but obviously not in the 200 Hz resolution spectrum). Such low frequency modulation

Fig. 6. Frequency spectrum of the current emission of the inductive charging platform at the PCC. The red dashed line marks the end of the supraharmonic range, while the colored markers identify the origin of the spectral components.

was reported in [25] as well. Although the effect discussed in the present paper is still the result of the interference from different switching frequencies, as in [25] and [6], in this case there is a remarkable impact on the emissions as new, non-negligible, spectral components appear in the supraharmonics range. The resulting emission shows high magnitudes and must be taken into account when implementing mitigation strategies.

All the remaining peaks in the 2 kHz to 150 kHz range have low magnitudes, around 85 dB_{μA} at most. However, few more peaks can be identified. The spectral components from 2 kHz to 9 kHz are most probably produced by low order harmonics, so they are not strictly supraharmonics, as suggested in [26]. Moreover, the green triangles in Fig. 6 identify the emission due to f_{sw3} only, and its odd harmonics. The emission due to f_{sw2} is identified by black diamond signs. These spectral components are located at 75 kHz and 150 kHz but other peaks at 25 kHz and multiples can be spotted, since the DC/DC converter is composed by three legs switching at 25 kHz each. The magnitudes are low but they can still be identified. Finally, it is worth noticing that the spectral component due to the fluorescent lighting, discussed in III-A, is no longer visible in the current spectrum (nor in the voltage spectrum, shown in Fig. 7). The reason probably lies in a change of grid impedance.

C. Comments on Electromagnetic Compatibility

The EMC is defined as the ability of equipment or a system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment [28]. In order to ensure EMC between the devices, emission, compatibility, and immunity levels and limits should be respected. However, supraharmonic standardization is still deficient, not only from the point of view of measurement, but also from the EMC point of view. Compatibility levels for voltage distortion in the frequency range from 2 kHz to 150 kHz have just recently been included in IEC 61000-2-2 [27], but emission limits for unintentional emission have not been defined yet, with very few exceptions for some specific devices [29]. It is therefore not possible to

assess the EMC in the supraharmonic range and, in this section, only a qualitative comparison is made between the voltage emission and the compatibility levels defined in IEC 61000-2-2.

Fig. 7 shows the voltage spectrum obtained from the same measurement interval employed in the previous section to obtain the current spectrum, as well as the compatibility levels from IEC 61000-2-2. Although it does not represent a compliance test, as no emission limits exist, it is interesting to compare the orders of magnitude of the emission. As it can be observed, the voltage emission is very similar to the current emission (Fig. 6). The same spectral components can be identified and they follow the same pattern as for the current. The same beat phenomenon is observed and the relative spectral components are again the most intense ones in the spectrum. The black dashed line shows the compatibility levels. As it can be seen, the spectral components corresponding to the switching frequencies are all well below the compatibility levels. However, the peaks resulting from the beat phenomenon can be as high as the compatibility levels and, in some cases, even sensibly higher, especially towards the high-frequency side of the spectrum (e.g. 143.1 kHz). This confirms the need of more standardization in the range from 2 kHz to 150 kHz. It is also an indication that the beat phenomenon can produce effects not only in the low interharmonic range, but also in the supraharmonic range, producing emission that is far from being negligible. Moreover, it can be seen that the intensity of the spectral lines does not decrease with the frequency, meaning that it is in principle possible to observe effects even at higher frequencies.

IV. CONCLUSIONS

In this work, the emission of an electric bus inductive charging in the range from 2 kHz to 150 kHz has been studied, identifying the cause of the spectral components that produce the most important impact. By knowing the construction details of the charging system, it has been possible to identify the spectral components corresponding to the switching frequencies of the involved converters. Moreover, other intense spectral components have been identified in the frequency spectrum.

Fig. 7. Frequency spectrum of the voltage emission of the inductive charge at the PCC. The red dashed line marks the end of the supraharmonic range, while the colored markers identify the origin of the spectral components. The black dashed line corresponds to the compatibility levels, taken from IEC 61000-2-2 [27].

These components represent the most important emission of the systems and their cause has been traced back to the interference between the switching frequencies of the various converters, with a phenomenon similar to the beat effect. Interference between switching frequency components results to be important not only as low frequency interharmonics but also in the supraharmonic range, producing distortion levels that could be as high as the compatibility levels for this range, and even more. Moreover, these components do not decrease in magnitude with the frequency, having the potential of creating distortion even at higher frequency ranges. Without knowing the exact topology of the charger, it would have not been possible to distinguish between switching frequency emissions and interference among them. Mitigation strategies for this frequency range are still an unexplored research topic, but it is clear that this interference effect must be taken into account for the mitigation as well as for the emission modeling. This work represents the first step of a complete characterization and modeling, which in the future should include the study of other factors that could affect the emission, such as the misalignment of the IPT, which is a crucial parameter for inductive charging.

ACKNOWLEDGMENT

The authors would like to express gratitude to Malaga City Council, ENDESA, MANSEL Electricidad y Montaje S.L., and Empresa Malagueña de Transporte S.A.M. for the permission to use the bus and other equipment to carry out the tests.

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