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Combining single-phase and three-phase EV charging: a way for increasing harmonic hosting capacity

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Executive Summary

The computation of the harmonic hosting capacity requires proper vector summation of the charging currents at the PCC and prior knowledge of the driving point/loop impedance of the network. This paper shows the harmonic magnitude reduction effect introduced by the addition of a new EV on the network while an existing EV is charging. The supraharmonic components are limited to the circuit between the EVs, while only lower-order harmonic components propagate toward the PCC. The impact of single-phase and three-phase charging on the network is discussed. The paper also discusses the reduction in the computed harmonic hosting capacity if the summation law as per IEC 61000-3-6 is used.

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Keywords: Electric Vehicles, Electromagnetic Compatibility, Modelling & Simulation, Smart grid integration, Smart charging.

1 Introduction

The overall household electricity consumption from 2001 to 2021 in Sweden has shown a declining trend except for the year 2021, which saw an increase in the overall household consumption[1]. A look at the electric vehicle (EV) adoption statistics shows an increase in the adoption of electric vehicles in 2021 with an 18% increase in the number of new EVs registered and the number of battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs) accounting for 43% of the new registrations [2]. The trend has accelerated with favourable policy interventions, and BEVs and PHEVs now account for 56% of the new registrations [3].While the overall electricity consumption in Sweden has a strong dependence on the severity of the winter, the increase in the number of electric vehicles could also be considered among the reasons for the reported increase in electricity consumption. Thus, with an increased proliferation of EVs, the impact on the low voltage (LV) grid and especially the propagation of harmonics generated has been a topic of increased scrutiny over the years.

Accurate characterization of these distortion sources is essential for assessing the harmonic hosting capacity of the low-voltage grid. Harmonic hosting capacity refers to the maximum allowable injection of harmonic currents or voltages at the point of common coupling (PCC) without violating established power quality standards[4], [5], [6], [7], such as those defined in IEC 61000-2-2 [8]. With the increasing penetration of EVs (characterized by non-linear and switching behaviors[9], [10], [11], [12]), quantifying hosting capacity becomes critical for network planning and operational stability. This assessment must consider the aggregate harmonic emissions, the interaction between harmonic, interharmonic, and supraharmonic components introduced by multiple simultaneous EV charging events, and the impact on the grid impedance by the integration of electric vehicles on the grid.

The subject of harmonic hosting capacity evaluation has been extensively discussed in the literature [13], [14], [15], [16], [17], [18], [19], [20], [21]. In [20] a review of tools used for hosting capacity has been provided. Deterministic methods for harmonic hosting capacity studies, such as constant emission and time-series approaches, model power electronic loads as harmonic current sources without considering their impact on grid impedance[16], [22]. As the emission profiles are fixed or based on specific measurements, dynamic interactions between loads and the grid are neglected, potentially limiting the accuracy of the results under high penetration of power electronic devices. Similarly, optimization-based methods [18],[19] and harmonic power flow-based approaches typically model power electronic loads as current sources and assume a fixed grid impedance, thereby sharing the same limitation of neglecting the dynamic interaction between loads and the network. The proposed approach expands on the approach proposed in [13]offers measurement-driven, statistically robust, and computationally efficient means to evaluate harmonic hosting capacity compared to deterministic, optimization-based, or harmonic power flow methods. By relying on real-world emission variability and directly comparing it with available margins, it provides a transparent and conservative estimation of the maximum number of vehicles that can be connected without complex modeling assumptions.

The voltage waveform distortion at the point of common coupling (PCC) on the LV grid is a function of the following components:

- Aggregation of local emission from the loads connected at the PCC and the grid impedance.
- The background waveform distortion propagated from the upstream network.

EVs need to convert the AC input into DC to charge the batteries onboard and need to comply with the recommendations in [23]. For this, the EVs employ an active front-end converter for both single-phase and three-phase charging of the onboard battery from a MODE 3 electric vehicle supply equipment (EVSE).

The input current of a controlled single-phase rectifier is given by the following expression[24]:

$$I_{1\emptyset} = I_1[\sin(\omega t - \alpha) + \frac{1}{3} sin3(\omega t - \alpha) + \frac{1}{5} sin5(\omega t - \alpha) \dots] \quad (1)$$

where I_1 is the peak fundamental current and α is the delay or firing angle of the semiconductors.

The input current of a fully controlled three-phase rectifier is given by the following expression [24]

$$I_{3\emptyset} = I_1[\sin(\omega t - \alpha) - \frac{1}{5} sin5(\omega t - \alpha) - \frac{1}{7} sin7(\omega t - \alpha) + \frac{1}{11} sin11(\omega t - \alpha) + \frac{1}{13} sin13(\omega t - \alpha) \dots] \quad (2)$$

This indicates that the emitted 5th and 7th harmonic are in phase opposition and may get cancelled. This evaluation may lead to the conclusion that the hosting capacity of the LV network may be higher for the 5th and the 7th harmonic due to the cancellation effect. Measurements undertaken at the charging facility at Luleå university of technology and shown in the polar plot in Fig. 1 indicate this to be true for the 5th harmonic, but to a lesser extent for the 7th harmonic current component.

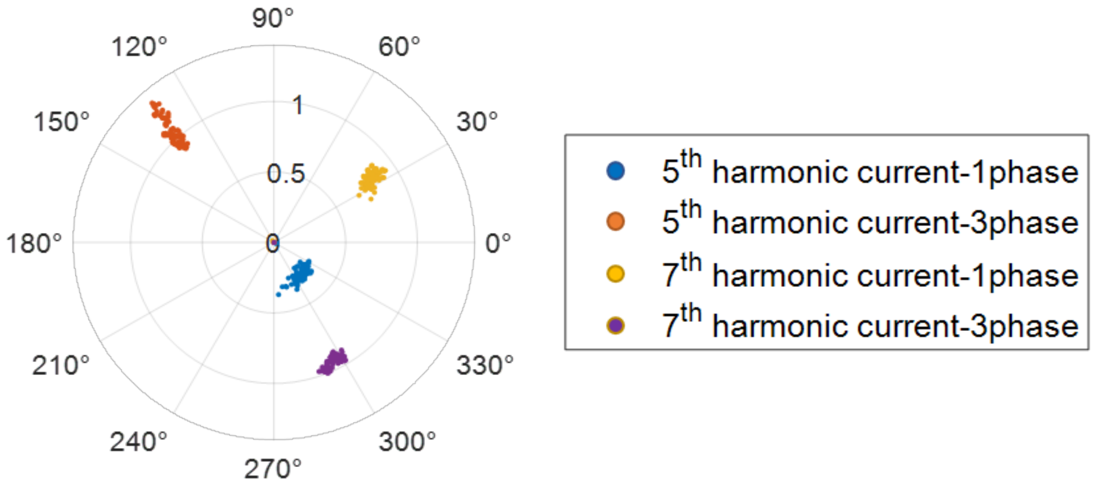

Fig. 1 Polar plot of 5th and 7th harmonic current components during single and three-phase EV charging

The summation law proposed in IEC 61000-3-6 [25] is a thumb rule and can give incorrect results as it can sum the components that are in phase opposition. Thus, it is proposed to analyze the impact of phase angle variation based on measurements and perform the assessment stochastically to consider the variations in emissions during EV charging. The mathematical analysis is performed in Section III on combined single-phase and three-phase charging. This is preceded by the analysis of the measurements undertaken in the charging facility at Luleå University of Technology in Section II. The computation of hosting capacity limits is performed in Section IV followed by a discussion on the observations and the chosen reference impedance.

2 MEASUREMENTS

Measurements were carried out on an EV capable of both single-phase and three-phase charging. The vehicle is capable of accepting charge from the grid at the rate of 22 kW per hour. The charging current for three-phase charging was however limited to 16 A per phase or 11 kW. The single-phase charging was facilitated with the control box provided by the car manufacturer allowing the EV to be charged at the rate of 1.8 kW. The state of charge of the vehicle is also monitored throughout the charging phase through the information displayed on the driver information system on the EV. The input voltage from the grid and the charging current was monitored with the help of a power quality monitor capable of sampling the input waveform at 1 Ms/sec and 500 ms of data was recorded every minute. The background voltage recorded shows the presence of the 7th, 5th harmonic, and 3rd harmonic as the dominant components at 1.5%, 1.3%, and 0.5% of the fundamental respectively. The spectrogram of the recorded voltage waveform does not show any significant frequency component within the 2 kHz to 150 kHz band. The measured and calculated value of cable impedance at the point of connection is in close agreement at about 0.353 mΩ (resistance) and 0.029 mΩ (reactance).

3 Charging-Single Phase

The permissible distortion of the current waveform for charging currents < 16A is listed in IEC 61851-21-1 [23]. The standard recommends the limits identified in IEC 61000-3-2 [26] for current harmonics injected into the grid. Fig. 2(a) shows the box plots of harmonic components of the current waveform during the charging duration against the limits in [6]. The box plot has been modified and the whiskers represent the 99 percentile values of the variation in the harmonic profile of the charging current for the corresponding harmonic order. The corresponding voltage waveform distortion compared against IEC 61000-2-2 limits specified in [23] were all within acceptable limits. Fig. 2(b) shows the spectrogram of the harmonic components visible in the 2 to 150 kHz band. The converter's switching frequency can vary between 59 and 68 kHz throughout the charging sequence as the state of charge increases from 17% to 85%. This variation of the switching frequency has been identified in [27] as the frequency dithering technique, used to spread the energy over a range of frequencies and thus reduce the overall profile of the emitted supraharmonic distortion.

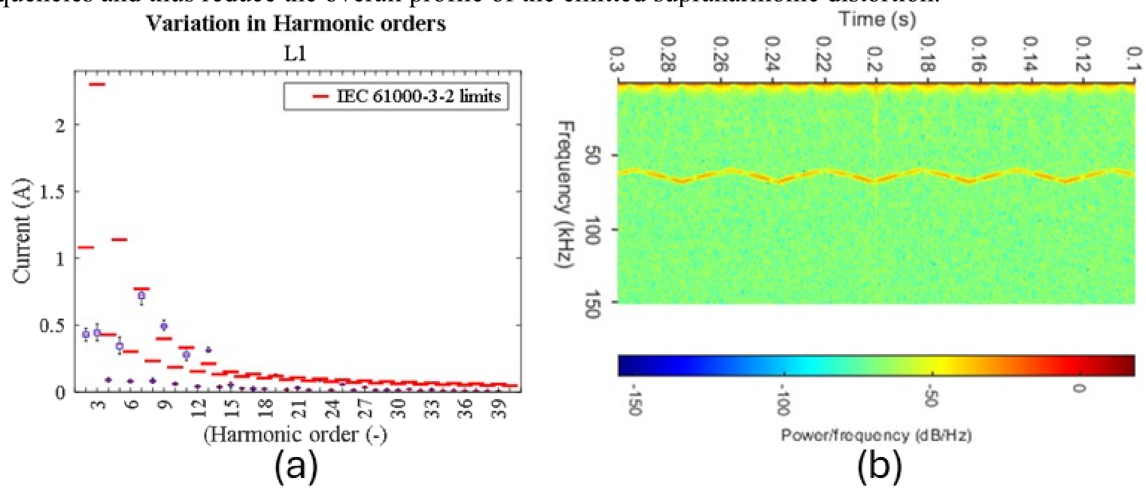

Fig. 2 (a) Grouped harmonic components of the single phase charging current (b) Spectrogram of the harmonic components in a 2-150kHz band for single phase charging current

4 Charging Three-Phase

Fig. 3(a) shows the observed variation in the harmonic components of the current waveform during three-phase charging. Comparison against the limits in [26] shows the violation of the 11th, 13th 19^{th,} and 23rd harmonic orders. The dominant components observed are of the order 6n±1 corresponding to the operation of a 6-pulse converter [28]. The 200 Hz grouped components within the band 9 to 150 kHz band can be seen in Fig. 3(b). As no standard presently identifies the distortion limits in this band, the limits have been derived by taking the compatibility limits identified in [23] and the reference impedance of the artificial mains network used in testing as per IEC 61000-4-7 and extending it to the 9-150 kHz frequency range [29]. The spectrogram of the voltage and the current waveforms in the 2 to 150 kHz band shows a similar pattern as shown in Fig. 2(b) and hence not repeated here for brevity.

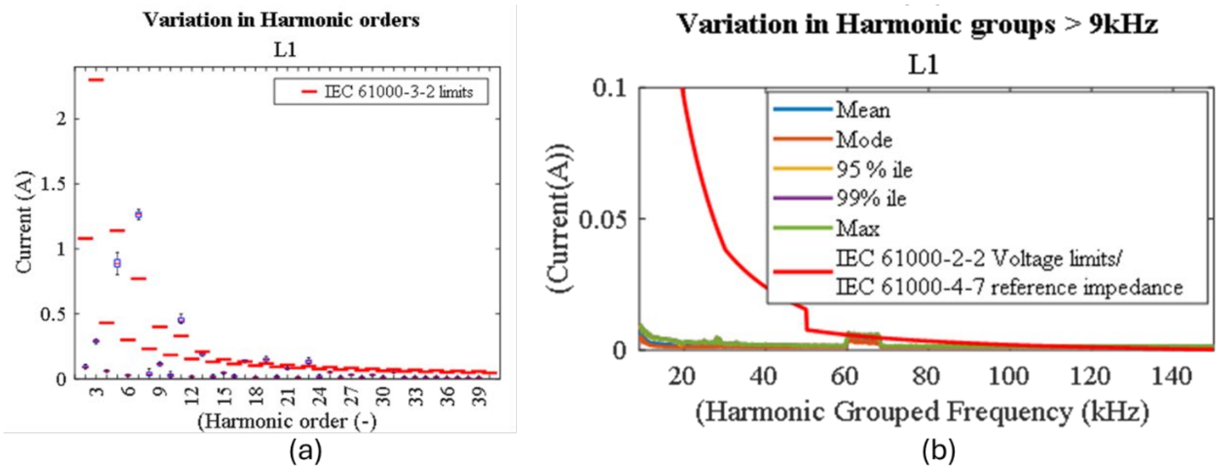

Fig. 3(a) Grouped harmonic components of 3-phase charging current (b) 200 Hz grouped harmonic components in the band 9-150kHz compared against limits from IEC 61000-2-2 and ref. impedance of IEC 61000-4-7

5 Combined single-phase and three-phase charging

The report [30] suggests for multiple loads in parallel on the network, the vector addition of the different harmonic components to study the net impact on the LV network. The report does not consider the impact of propagation of the current harmonic components to the neighbouring devices because of the impedance offered. The impact of the propagation of the supraharmonic components in a LV network has been studied in [31] for LED lamps and a photovoltaic (PV) system wherein the impact of the impedance of the devices on the network has been brought forth.

Fig. 4(a), shows two EVs, EV1 and EV2, charging on the LV grid. EV1 is undergoing single-phase charging and EV2 is charging through a three-phase charger. Consider phase L1 as the common phase between the two EVs charging on the grid. If I_{h1} is the emission at frequency h reported for EV1, then I_{hn1} is the portion of the harmonic components of current that will flow to the neighboring EV and $I_{g1}(h)$ is the contribution flowing into the grid. Similarly $I_2(h)$, $I_{hn2,}$ and $I_{g2}(h)$ are components of EV2.The effective impedance of the EV is unknown and hence the driving point impedance of the filter has been used in this study. Fig. 4(b) shows the driving point impedance of a typical filter used in an EV [32] . The portion of the harmonic current from EV1 that will flow toward the grid can be computed as

$$I_{g1}(h) \ = \left[\frac{Z_{eff2}(h)1 \ || \ Zs(h)}{Zs(h)}\right] * I_1(h) \tag{3}$$

$$I_{g2}(h) \ = \left[\frac{Z_{eff1}(h)1 \ || \ Zs(h)}{Zs(h)}\right] * I_2(h) \tag{4}$$

where $I_1(h)$ and $I_2(h)$ are the measured harmonic components at frequency h. Z_{eff2} is the filter impedance seen by EV1 towards EV2 and Z_{eff1} is the filter impedance seen by EV2 towards EV1. $Z_s(h)$ is the cable impedance identified in the measurements section. The net emission seen at the PCC is

$$I(h) = I_{g1}(h) \ + \ I_{g2}(h) \tag{5}$$

Since, the same EV is used in the study,

$$Z_{eff1} \ = \ Z_{eff2} \tag{6}$$

Since the occurrence of two identical EVs simultaneously charging on the same grid may be rare, the values of $I_1(h)$ and $I_2(h)$ and the corresponding harmonic angles are derived stochastically from the distribution of the measured harmonic currents for single phase and three phase charging.

6 Hosting Capacity

Paper [4] defines the harmonic hosting capacity as 'the maximum value of the harmonic current of order h that will drive the harmonic voltage to a boundary of maximum acceptable distortion' and suggests the methodology for the estimation of the harmonic hosting capacity. The minimum value of the hosting capacity current of order h (Hosting Capacity -Min) is the current in phase with the distorting current that will drive the harmonic voltage to the harmonic voltage limit. The maximum harmonic hosting capacity current (Hosting Capacity-Max) is the value of current in phase opposition to the measured value of the harmonic current to drive the harmonic voltage to the corresponding harmonic voltage limit [4]. The driving point impedance as seen by the loads on the grid is unknown and hence the impedance of the artificial mains network as defined in [29] is used here as the reference impedance. The measurements of the current drawn by the EV, shown in Fig. 2 and Fig. 3 are used as the background distortion and the possibility of connecting additional loads (single phase or three phase) is then assessed using the approach from [13].

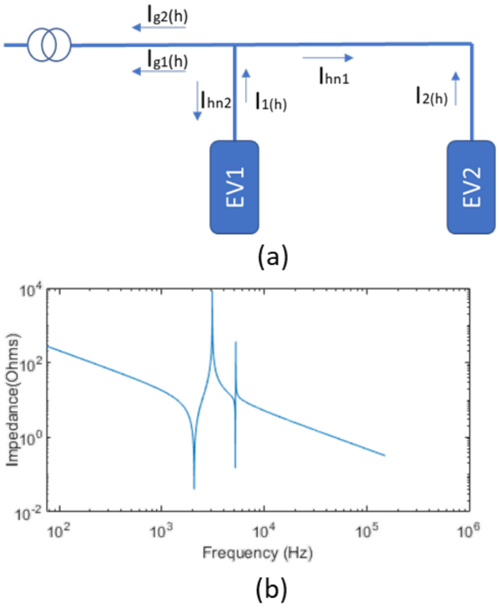

Fig. 4 (a) Network configuration of two EVs charging side by side (b) Driving point impedance computed for the input filter of the EV.

Fig. 5 shows the 99th percentile grouped values of the harmonic emission for phase L1 of a three-phase charging session. As seen in Fig. 5, the minimum hosting capacity is exceeded for the 7th harmonic, thus indicating that no device with the same phase angle could be connected here. A similar observation can be made for the supraharmonic components where the hosting capacity limits are violated for the range 60 kHz to 68 kHz.

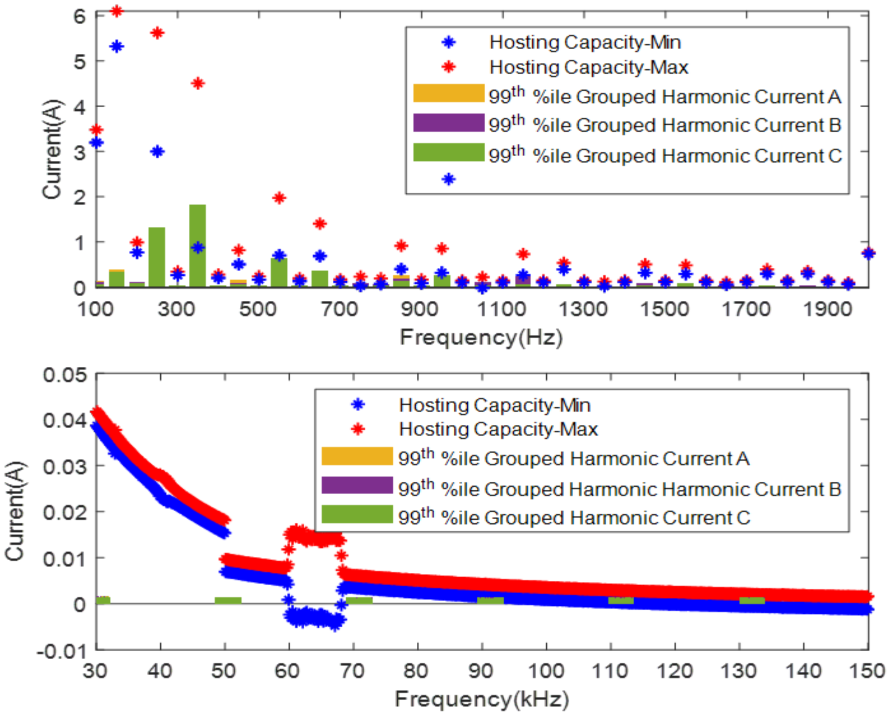

Fig. 5 99th percentile values of the grouped harmonic current components against the hosting capacity (Min) and (Max) for three-phase charging

Fig. 6 shows the 99th percentile grouped values of the computed harmonic emission for the combined charging of a single-phase charger and three-phase charger for phase L1. Comparing Fig.5 and Fig.6, an improvement in the hosting capacity for the 5th and the 7th harmonic components is observed with bandwidth being available for the connection of other devices. The minimum hosting capacity limit is now exceeded for the triplen harmonic components (9th ,15th and 27th.) These components will not propagate to the upstream network for a delta-star configuration of the feeding transformer. It is observed that switching frequency components between 60 and 68 kHz as shown in Fig. 5 are not propagating to the grid but are confined to the circuit between the connected EVs. However, components in the band 7 kHz -12 kHz have risen substantially, but not violating the limits. This impact can be understood as an effect of resonance conditions being created between the source impedance and the filter impedance. The hosting capacity (HC-Comb- Min) and (HC-Comb-Max) in the band 30 to 150 kHz is positive and is available for other devices to be connected to the grid. It is thus observed that the addition of the second EV results in the damping of the harmonic components in the range 30 to 150 kHz on the LV network.

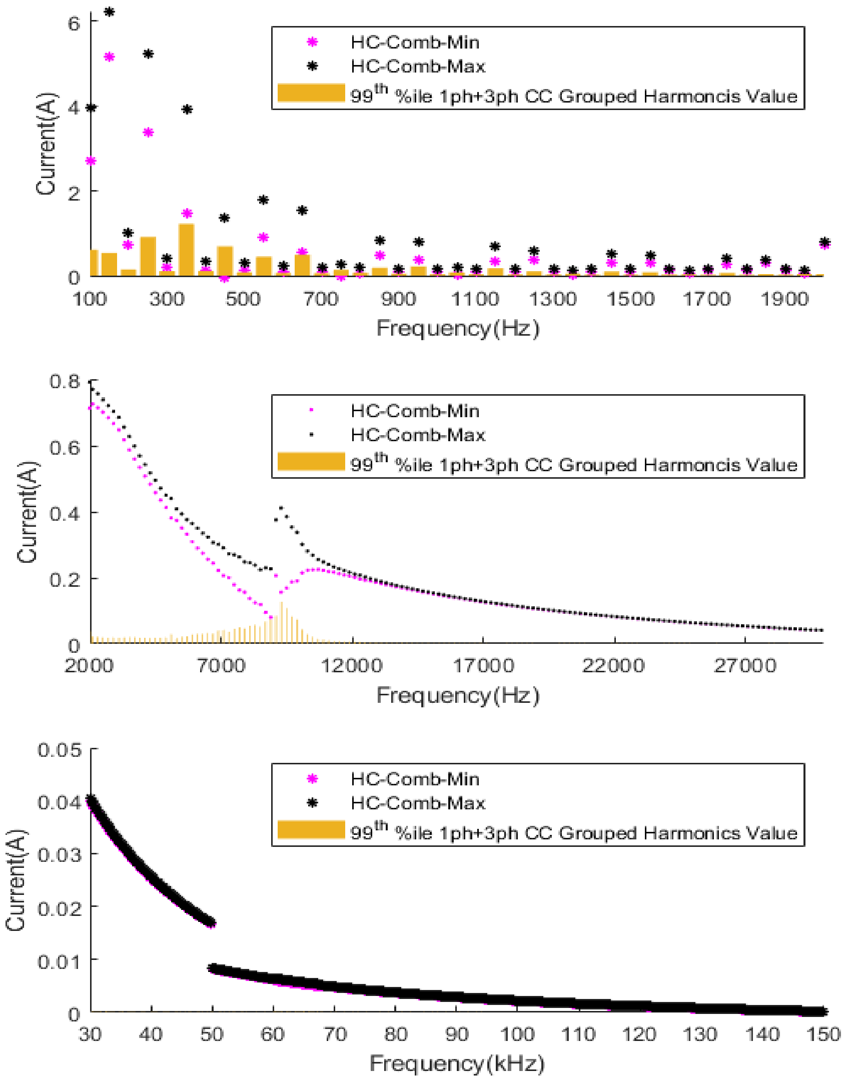

Fig. 6 99th percentile grouped values of the harmonic current components at PCC against the hosting capacity (Min) and (Max) for phase L1 with combined 1 and 3 phase charging

Reference [25] proposes a summation method for the summation of harmonic components of the current based on exponents to account for variations in phase angles. Table 1 shows the difference between the lower order hosting capacity limits obtained by the method of exponents, as in [5], and through vector summation with the inclusion of filter impedance.The hosting capacity for the 7th harmonic order is higher when determined with the vector summation as against through the method of exponents. Additionally, because of the combined charging, the hosting capacity for the 7th and the 5th order has increased when compared to the minimum limits during only three-phase charging. For the triplen harmonic components, the minimum harmonic hosting capacity limit for combined charging is lower than the one for only three-phase charging. Fig. 7 shows the hosting capacity limits (HC-Comb-Min-3-6) and (HC-Comb-Max-3-6), obtained with the method proposed in [5]. For the sake of clarity the hosting capacity limits obtained in Fig. 6 have been plotted in Fig. 7 as (HC-Comb-Min-VS) and (HC-Comb-Max-VS). It is observed that the resonance condition, as identified between 7 and 12 kHz, is completely missed by using the method of exponents, and hence, the hosting capacity limits are higher for this range. For the range between 30 and 150 kHz, the limits are lower than the one computed through vector summation, even though these components are expected to get filtered out.

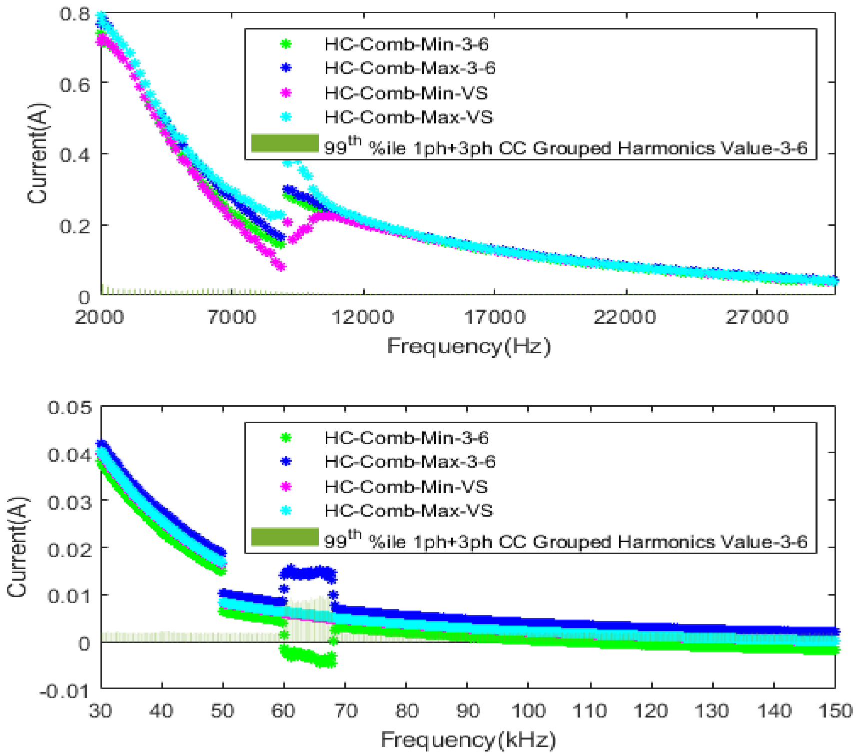

Fig. 7 99th percentile grouped harmonic current components at PCC using IEC 61000-3-6 summation law against Hosting capacity (Min) and (Max) with combined 1 and 3 phase charging

Table 1 Computed minimum Hosting Capacity Limits for lower order harmonics

Charging Mode	Low Order Harmonic Order					
	3	5	7	9	11	13
Combined 1 and 3 Phase Charging (3-6)	5.06	2.89	1.21	0.02	0.72	0.595
Combined 1 and 3 Phase Charging (Vector Sum)	5.17	3.39	1.46	-0.033	0.89	0.55

7 Discussion

The study performed in [33] for the range 2 to 9kHz suggests the loop impedance values of the LV networks are lower than the limit values proposed in IEC [29]. Another study on the loop impedances of the network carried out in the Netherlands in the range 9 to 150 kHz suggests that the loop impedance values are lower than the CISPR16-1-2 artificial mains network impedance [12]. Due to the lack of such data for Sweden, the impedance from [29] was chosen as a reference, with impedance values in between those suggested by IEC 60725 and CISPR16-1-2. The availability of such information will help ascertain the correct limits for the permissible harmonic distortion from EVs on the LV networks.

Through the analysis presented, the impact and existence of resonance conditions on the LV network can be observed. The study only includes the impedance offered by the filter, the true impedance offered by the EV needs to be ascertained for a detailed study. Developing knowledge on the impedance offered by power electronic converters under different network and operating conditions is an active area of research [15].

Conclusion

The mathematical analysis suggests an optimistic outcome and the analysis as per [25] is more conservative. A stochastic analysis based on actual measurements reflects the true aggregation of the emissions at the PCC. It also helps in understanding and studying the impact of resonances on the LV network.

Acknowledgments

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