Analyzing Phase Imbalance in Smart Charging of Multiple EVs: An Experimental Approach

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Abstract

The increasing penetration of electric vehicles (EVs) is causing uneven loading in low voltage distribution networks, primarily due to variations in smart charging rates and simultaneous charging of single-phase and three-phase EVs. This study experimentally analyzes three mainstream EVs (Renault Zoe R90, Peugeot e-2008, Nissan Leaf e+) charging concurrently, with the Zoe and e-2008 using three-phase power and the Leaf using single-phase power. Smart charging capabilities are used to gradually increase charging current from minimum to maximum power for each vehicle. Harmonic, current, and voltage measurements were taken at the point of common coupling using a power quality harmonic analyzer. The results reveal significant harmonic imbalances in three-phase networks, particularly when different types of EVs are charged simultaneously. This highlights the necessity for active load management to ensure EV charging adheres to industry standards and recommendations, such as IEC 61000-3-12 for harmonic emissions and CIGRE C4.07. Such active management strategies can mitigate the negative impacts of uneven loading and ensure the stability and reliability of power distribution networks as EV adoption continues to grow.

1 Introduction

Governments worldwide have established ambitious targets to achieve climate neutrality within the next few decades, with the transport sector being a primary focus due to its significant contribution to greenhouse gas emissions [1]. The transition to electric vehicles (EVs) is widely regarded as a key strategy for reducing emissions within the road transport sector, alongside reducing travel frequency and distance, and promoting the use of alternative low-carbon modes of transport such as buses and trains. However, the widespread adoption of EVs necessitates a harmonious integration between existing power grids and EV charging networks [2]. Successful electrification hinges on various factors, including the pace of grid infrastructure upgrades, EV sales volume and geographical distribution, the development of EV charging infrastructure, regulatory decisions, and prevailing economic conditions [3, 4].

EVs are projected to significantly impact electrical distribution networks, potentially exceeding the rating of grid components due to their direct connection at the distribution level [5, 6]. Notably, high EV charging demand at scale can violate the thermal limits of distribution feeders and transformers, reducing their operational lifespan [7]. This increased demand may also elevate peak loads, introducing uncertainties that can adversely affect market economic operation and grid stability [8]. Furthermore, the primary operating voltage of networks may exceed thresholds at certain EV penetration levels due to increased power flow and subsequent voltage drop [9]. Additionally, EVs may, under specific conditions, exert a greater influence on secondary voltage than primary voltage due to heightened short-circuit levels and deteriorated power quality resulting from harmonics generated by EV chargers [10, 11].

Smart charging is an emerging solution to manage the impact of EV charging on power grids [12, 13]. This approach leverages the flexibility of charging, which stems from the difference between the time a vehicle is parked and the time it actually needs to charge [14]. In smart charging, the charging rate of vehicles could be modulated within minimum and maximum charging currents. It is noteworthy that the minimum AC charging current is around 6A for all EVs, while the maximum charging rate is typically 16A or 32A depending on the vehicle model [15]. Our previous research shows that the harmonic content of EVs significantly increases when the charging current reduces. Therefore, smart charging will introduce additional harmonic issues [15].

Depending on the network topology and vehicle type, EVs could be charged with a three- or single-phase supply (see [16] for a sample three-phase residential unit). In addition, when smart charging is applied to a group of EVs, the consequent charging profile may lead to an increase in imbalances in LV networks, especially in weaker rural areas. Therefore, it is critical to address phase imbalances, and the permissible voltage imbalance in low voltage distribution networks is typically capped at 2% [17]. Uneven loads like EVs can create unbalanced harmonic currents, leading to unbalanced harmonic voltages. Currently, the assessment of harmonic imbalance is not typically included in the analysis and design of distribution systems. Existing standards only focus on evaluating the fundamental voltage imbalance. A limited number of studies have considered the evaluation of unbalanced harmonics. For instance, [17] examines the imbalance characteristics of

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Table 1 Overview of technical specifications for EVs.

EV Model	Model Year	Nominal Battery Capacity (kWh)	Practical Charging Current Range (A)	Charging Type (AC)	Practical Charging Power Range (kW)	Connected Phase
Renault Zoe R90	2018	44.1	5.91 to 31.10	3-ϕ	0.00 to 21.46	All Phases
Nissan Leaf e+	2022	62	5.90 to 28.39	1-ϕ	1.36 to 6.530	Phase A
Peugeot e-2008	2022	50	5.83 to 15.23	3-ϕ	4.02 to 10.51	All Phases

Fig. 1. Overview of the experimental setup.

fundamental and harmonic currents in three-phase EV battery chargers through experimental testing on two different types of EVs. A novel framework which coordinates compensation for imbalance and harmonic emissions within secondary distribution networks is presented in [18]. This framework leverages the inherent capabilities of EVs and their charging infrastructure. EV chargers are strategically utilized as power line conditioners, facilitating the injection/absorption of active and reactive power, and enabling control over the harmonic current spectrum. The proposed model integrates this functionality with EV charging management strategies.

Existing literature often focuses solely on harmonic levels, as utilities are typically required to maintain these levels below a specified limit. However, this approach can overestimate harmonic issues if the diversity of vehicles is not considered. To address this limitation, our paper utilizes both harmonic magnitude and phase angle data of three different EV models with very different characteristics, offering a more accurate assessment of the cancellation effect.

This paper presents an experimental approach, offers harmonic measurements of three mainstream EVs charging at the same time and provides an experimental analysis of harmonic phase imbalances. To the best of the author's knowledge, this is the first study presenting an actual dataset on harmonic imbalances for a varying range of smart charging currents.

2 Experimental Overview

The EV charging experiments were conducted at the Energy System Integration Lab (SYSLAB) at the Technical University of Denmark (DTU) [19]. Three distinct pure battery EVs, namely, the Renault Zoe R90, Nissan Leaf e+, and Peugeot e-2008, were selected for testing. The technical specifications of these vehicles are detailed in Table 1.

The selection of these specific vehicles was motivated by the desire to replicate real-world scenarios where harmonic imbalances manifest in three-phase networks. Notably, the Nissan Leaf e+ is a single-phase vehicle, while the Renault Zoe R90 and Peugeot e-2008 are equipped with three-phase charging capabilities. This deliberate diversity in charging configurations aims to capture the complex interactions and potential challenges arising from the simultaneous charging of multiple EVs with varying power requirements within a shared network.

The experimental setup, conducted at the SYSLAB facility at DTU, employed three distinct AC smart chargers, each paired with a corresponding EV model: the Fronius Wattpilot for the Nissan Leaf e+, the Zaptec Pro for the Peugeot e-2008, and the Keba KeContact P30 for the Renault Zoe R90. These chargers, each capable of delivering a maximum current of 32A per phase, were equipped with functionalities enabling both scheduled charging and dynamic power modulation. Configuration of the chargers was achieved through their respective interfaces: the Solar.wattpilot mobile application for the Fronius Wattpilot, the Keba eMobility App for the Keba KeContact P30, and a dedicated web-based interface for the Zaptec Pro. Importantly, these chargers offered granular control over smart charging rates, permitting adjustments in 1A increments within the predefined minimum and maximum current boundaries.

To ensure accurate and reliable data acquisition, the harmonic content generated during the charging process was meticulously captured and analyzed using either a Yokogawa WT500 power analyzer or a Fluke 435 Series II power quality analyzer. Both instruments had undergone recent calibration and certification, guaranteeing the validity of the collected measurements. Harmonic analysis was extended up to either the 31st or 49th order, contingent upon the specific capabilities of the analyzer deployed in each instance. In total, four power quality analyzers were strategically integrated into the experimental setup: one dedicated to each of the three EVs and an additional analyzer strategically positioned at the point of common coupling (PCC) to monitor the aggregate harmonic behavior of the system. Selected photos of the equipment and vehicles used in the experiments are shown in Fig. 1.

Table 2 Charging schedule for four different experiments. Nissan Leaf e+ charging rate follows 3A increments (e.g. 6, 9,...,32)

Experiment ID	Electric Vehicle	Charge Rate (A)	Duration (min)
1	Renault Zoe R90	6	0-6
	Peugeot e-2008	6	
	Nissan Leaf e+	6-32	
2	Renault Zoe R90	9	6-12
	Peugeot e-2008	9	
	Nissan Leaf e+	6-32	
3	Renault Zoe R90	12	12-18
	Peugeot e-2008	12	
	Nissan Leaf e+	6-32	
4	Renault Zoe R90	15	18-24
	Peugeot e-2008	15	
	Nissan Leaf e+	6-32	

In our prior investigation, we demonstrated that the harmonic content generated by onboard EV chargers (also employed in this study) exhibits a notable increase as smart charging rates are decreased [15]. For instance, the total harmonic distortion (THD) associated with the Nissan Leaf e+ was observed to escalate from approximately 3.8% at a charging rate of 32A to 10% at a charging rate of 6A. Similarly, the THD of the Renault Zoe demonstrated an inverse correlation with the smart charging rate, fluctuating between 4% and 13.5% as the charging rate was reduced from its maximum to its minimum value.

It is crucial to acknowledge that the number of potential charging combinations, where each vehicle's charging rate is to be incremented by 1A at each step, could reach a considerable magnitude, calculated as follows:

$$\prod_{i=1}^{3}(\lfloor \mathrm{MaxChargeRate_i} \rfloor - \lceil \mathrm{MinChargeRate_i} \rceil)$$

Based on the data presented in Table 1, this translates to a total of $(31-6) \times (28-6) \times (15-6) = 4950$ distinct combinations. Such an extensive array of possibilities renders an exhaustive experimental exploration impractical. Consequently, a decision was made to conduct four distinct charging experiments, as outlined in Table 2, to capture a wide range of charging rates. Each experiment was designed to encompass a duration of six minutes, with the three-phase vehicles (Renault Zoe and Peugeot e-2008) maintaining a constant charging rate throughout. Conversely, the charging rate of the single-phase vehicle (Nissan Leaf e+) was increased from 6A to 32A in 3A increments, with each charging rate maintained from thirty seconds to one minute. This experimental design aimed to find an optimal balance between capturing the dynamic interplay of harmonic content and smart charging rates while ensuring a feasible scope for subsequent analysis.

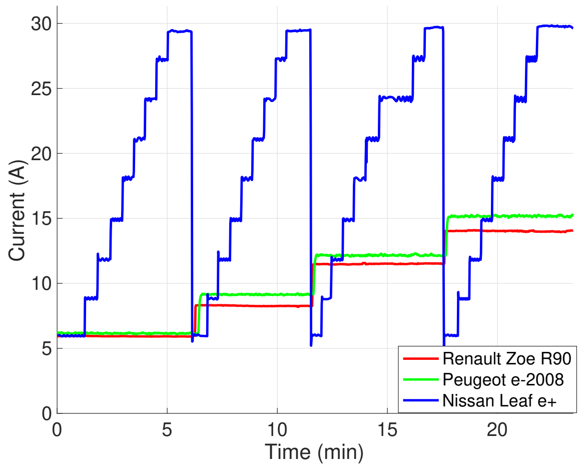

Fig. 2. Single phase charging current [A] of three EV models.

3 Results and Analysis

While Table 2 shows the intended set of experiments, in actual experiments, there could be slight variations in charging current due to the AC/DC conversion losses and the capability of the onboard charger to adjust the charging current to the exact set point (e.g. 9 Amps). Therefore, actual charging currents measured by each PQ analyzer is presented in Fig. 2. At higher charging currents, the actual rate is slightly lower than the rate set by the smart charger ($\leq 1A$). Moreover, from this plot, one could also notice the difference in response time of different onboard chargers. When the charge rates are increased, each vehicle responds with different time delays, and a detailed discussion on onboard charge response times can be found in [20]. Next, the current total harmonic distortion ($\mathrm{THD_I}$ (%)) of each EV is presented in Fig. 3. It can be seen that the $\mathrm{THD_I}$ emission of Peugeot e-2008 is consistently higher than the other two vehicles at almost all charging rates. Note that the first six minutes of the experiments correspond to the lowest charging rate for the three-phase vehicles. When this range is compared with the harmonic emission of Nissan Leaf e+, it can be observed that Nissan's harmonic emission stays significantly lower than the other two vehicles.

While Fig. 3 shows individual EV level harmonic emissions, total harmonic emissions per each phase at PCC will differ due to the summation of multiple harmonic content. When EV chargers from various manufacturers are combined, a wide range of harmonic patterns are expected. Due to the differences in these patterns, some harmonics may cancel each other out. This occurs when harmonics with opposing phases add up to a value smaller than their individual magnitudes. Evaluating this effect is still quite complex. However, the likelihood of cancellation increases with a larger number of EV chargers.

The current THD for each phase is presented in Fig. 4. In phases B and C, the measured THD (%) is the vector summation of Renault Zoe R90 and Peugeot e-2008. On the other hand, phase A represents the summation of three vehicles and exhibits a different pattern. It is also noteworthy that there is

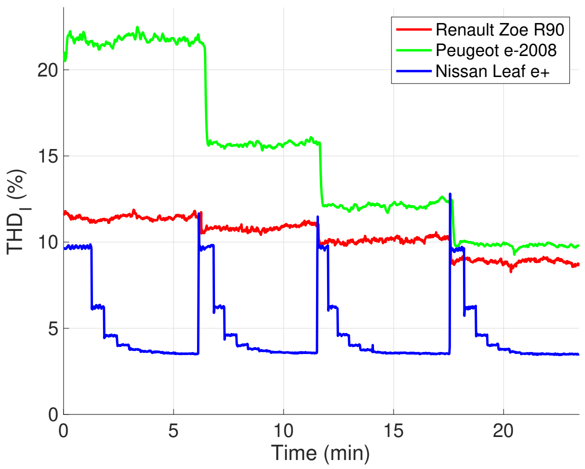

Fig. 3 Current Total Harmonic Distortion (%) for varying charging rates.

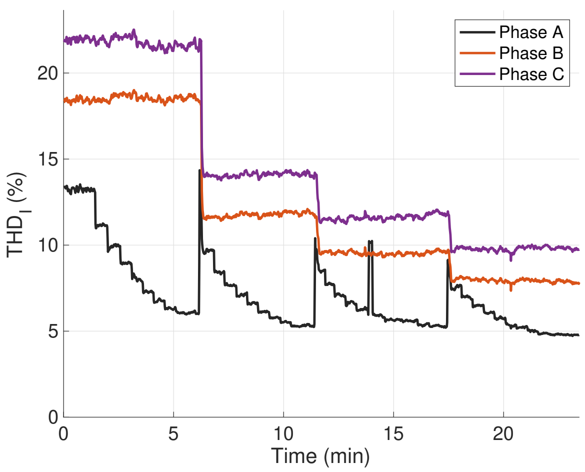

Fig. 4. Current Total Harmonic Distortion (%) for each phase.

a 120° angle difference between each phase. Hence, the summation of multiple harmonic sources experiences additional cancellation effects. This is one of the main reasons behind the difference in THD in phases B and C, even though the charging currents are the same, as shown in Fig. 2. It can be seen that the most dramatic harmonic imbalance occurs during the fifth-minute charging, where the THD of Phase A is 6.1%, and the corresponding THD in Phase C is around 22%.

As a last evaluation, Figure 5 presents the voltage THD (%) at each phase. As shown in Figure 5, unlike current harmonics, voltage harmonics do not cause power quality issues, and the voltage THD remains well below 5% industry standard levels [15].

4 Conclusions

This research examined harmonic phase imbalance issues through experiments involving three popular EVs (Renault Zoe

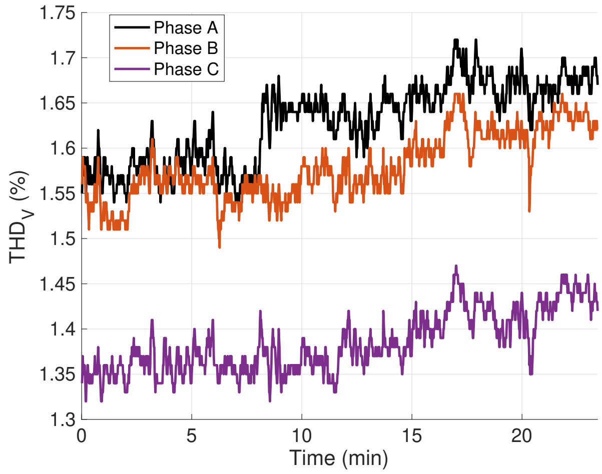

Fig. 5. Voltage Total Harmonic Distortion (%) for each phase.

R90, Peugeot e-2008, Nissan Leaf e+) charging simultaneously, using a combination of single-phase and three-phase power. Smart charging was applied to gradually increase the charging current for each vehicle, and the resulting harmonic, current, and voltage data was collected at the connection point to the power grid. The findings showed significant harmonic imbalances, especially when different EV types are charged at the same time.

Based on the results presented in this paper, a number of future research directions could be explored. First, there is a need to develop new metrics to quantify the impacts of harmonic imbalances that are similar to voltage imbalances. Second, the data presented in this study could be applied to residential (urban and rural) power networks in the presence of non-EV loads with different characteristics. Third, the results presented in this paper highlight the need for harmonics-aware smart charging strategies, which should not only support demand-side management but also mitigate harmonic distortions.

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