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Grid harmonic impact of multiple electric vehicle fast charging

Alexandre Lucas*, Fausto Bonavitacola, Evangelos Kotsakis, Gianluca Fulli

European Commission, JRC, Institute for Energy and Transport, PO Box 2, 1755 ZG Petten, The Netherlands

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ABSTRACT

Fast charging is perceived by users as a preferred method for extending the average daily mobility of electric vehicles (EV). The rated power of fast chargers, their expected operation during peak hours, and clustering in designated stations, raise significant concerns. On one hand it raises concerns about standard requirements for power quality, especially harmonic distortion due to the use of power electronics connecting to high loads, typically ranging from 18 to 24 kW h. On the other hand, infrastructure dimensioning and design limitations for those investing in such facilities need to be considered. Four sets of measurements were performed during the complete charging cycle of an EV, and individual harmonic's amplitude and phase angles behaviour were analysed. In addition, the voltage and current total harmonic distortion (THD) and Total Demand Distortion (TDD) were calculated and the results compared with the IEEE519, IEC 61000/EN50160 standards. Additionally, two vehicles being fast charged while connected to the same feeder were simulated and an analysis was carried out on how the harmonic phase angles would relate. The study concluded that the use of TDD was a better indicator than THD, since the former uses the maximum current (I_L) and the latter uses the fundamental current, sometimes misleading conclusions, hence it is suggested it should be included in IEC/EN standard updates. Voltage THD and TDD for the charger analysed, were within the standard's limits of 1.2% and 12% respectively, however individual harmonics (11th and 13th) failed to comply with the 5.5% limit in IEEE 519 (5% and 3% respectively in IEC61000). Phase angles tended to have preferential range differences from the fundamental wave. It was found that the average difference between the same harmonic order phase angles was lower than 90°, meaning that when more than one vehicle is connected to the same feeder the amplitudes will add. Since the limits are dependable on the upstream short circuit current (I_{SC}), if the number of vehicles increases (i.e. I_L), the standard limits will decrease and eventually be exceeded. The harmonic limitation is hence the primary binding condition, certainly before the power limitation. The initial limit to the number of chargers is not the power capacity of the upstream power circuit but the harmonic limits for electricity pollution.

1. Introduction

The paradigm change from centralised unidirectional electricity flow from plants to consumers into a distributed bidirectional electricity flow system, poses new challenges. These include the need for new operational strategies, models or simulation tools, and better infrastructure design (technological development and adaptation to a wider distributed grid). The interaction between distributed agents including smart houses or electric vehicles (EV), and the electricity grid has prompted the interest of researchers, industry and policy makers. These interactions between technical agents are supported by social/economic agents like prosumers, retailers, Distributed System Operators (DSO) or service companies, which are crucial to drive the interactions at a technical level. Standardisation requirements and a better understanding of interoperability phenomena, especially the impacts that large scale integration of distributed agents may have, are subjects of interest for industry, utilities, regulatory and policy making organisations. Among others, interoperability studies focus on enabling universal connectivity, batteries and EV interaction with the grid and other agents, and identifying gaps in standards or technologies.

Abbreviations: A_x, X axes component of vector A; A_y, Y axes component of vector A; B_x, X axes component of vector B; B_y, Y axes component of vector B; EV, electric vehicle; $E(\theta)$, phase angle mean value; I_1, fundamental current; I_h, individual current harmonic order; I_L, maximum demand load current at PCC; I_{ref}, reference current; I_{SC}, maximum short-circuit current at PCC; J, load; PCC, point of common coupling; PQ, power quality; PWHC, partial weighted harmonic current; R, resulting amplitude of a vector; R_X, resulting amplitude of vector X axes component; R_Y, resulting amplitude of vector Y axes component; RSCE, short-circuit ratio; SOC, state of charge; TDD, total demand distortion; THD, total harmonic distortion; THD_I, current total harmonic distortion; THD_V, voltage total harmonic distortion; Z, impedance; $U_{h\Sigma}$, resultant vector of a harmonic order; θ_h, phase angle of a vector related to the fundamental; $\sigma(\theta)$, phase angle standard deviation.

* Corresponding author. Tel.: +351961741327.
E-mail address: Alexandre.Lucas@jrc.ec.europa.eu (A. Lucas).

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The electricity industry has recommended Mode 3 EV charging (quick, single-phase or three-phase options) (IEC 61851) [1] as the preferred solution for all types of locations, making fast charging an important area to be addressed. Topics for the analysis by which EV charging impacts distribution networks can be listed as voltage regulation, harmonic distortion levels, unbalances, additional losses and transformers loss of lifetime. Battery chargers for EVs employ nonlinear switching devices which may result in significant harmonic voltage and currents injected into the distribution system. Literature reports different findings regarding the impact on power quality from EVs. Some authors state that distribution infrastructure can have limitations with EV charging supply even for relatively low EV penetration levels [2–5]. Other studies [6–11], suggest that low EV penetration levels, with normal charging rates, will have acceptably low harmonic levels and voltage variations, however fast charging rates could cause significant voltage harmonics and losses. Most of the studies tend to focus only on current harmonics, addressing as the main concern residential and normal chargers, as they are expected to have higher penetration. There is however, a very limited number of studies which analyse both voltage and current harmonics focusing on fast charging specifically performed in a cluster of chargers connected to the same feeder [12,13]. The motivation of the studies tends to be the same, high expected impact on energy demand and expected usage during peak hours.

Considerable literature focuses on the distribution networks especially residential networks [14,15], where EV charging could bring an additional severe power electronic load and associated power quality issues. The European standard for public power supply EN 50160 [16], sets conditions for: voltage magnitude variation, voltage harmonics, inter-harmonic voltage and voltage unbalance among others. All loads that are connected to the power network must provide a sufficiently low effect on the network, so that it does not cause a violation of the power supply conditions stated in this standard. This means that the EV chargers, once connected to a public network, must not influence the network operation to the extent that can cause deviation from the standard. In general, EV chargers have to fulfil requirements for loads that can be connected to an electric power network as described by the electromagnetic compatibility IEC 61000 series standards. These standards set the emission levels, including the harmonic currents or power factor that a charger is allowed to have. The standards applied to the low-power EV chargers are IEC 61000-3-2 [17] and IEC 61000-3-4 [18], which set limits to the harmonic emissions generated by the charger. Another study based on practical measurements of charging commercial EVs [8] presents a maximum THD_I of 17.3% for a level III charger at the end of the charge, and maximum of 19.2% for Level I and II also at the end. This publication acknowledges that TDD use would improve the conclusions regarding the distortion impact. Results from a case study in Portugal [9] found a THD_I of 11.6%, during the constant charging stage in a fast charging station integrated in a commercial facility.

A typical distribution network has a large number of different non-linear loads connected to it. Authors in Ref. [19] argue that adding EV chargers from different manufacturers may result in a variety of different harmonic patterns. The diversity of the patterns may lead to notable harmonic cancellation. This effect occurs when harmonics with different phase angles provide a sum in the magnitude that is smaller than the individual harmonics magnitudes. It is however rather complicated to evaluate this effect. Authors in Ref. [10] studying low voltage nonlinear loads also suggest that cancellation is more probable as the number of consumers and appliances increase. It has also been indicated that harmonic cancellation is more expected at higher harmonic orders, which can then account for the relatively minor THD_I decrease. In most papers, it is rather common that only the harmonics amplitude levels are observed, as the utilities are required to keep the harmonics levels under a given limit. Authors in Ref. [20] however note that if the diversity of chargers is not taken into account, the harmonic problems could be overestimated. One of the first papers in this area was actually presented by Ref. [21] where multiple different EV chargers in the network have been observed. It is reported, that 10% smaller harmonic current magnitudes were observed compared to the simple summing of magnitudes. Another study [22] applies a methodology which accounts for diversity of SOC and initial charging moments in California. The results indicate that accounting for variation in start-time and SOC in the analysis leads to reduced estimates of harmonic current injection. Authors argue that traditional methods do not account for these variations. Researchers show that from the point of view of the substation transformer, the impact of EV's is mainly one of power and energy, rather than harmonics. Analysis with real and imaginary components for each harmonic has been described in Ref. [7] which analyses 20 kW h charges and reports a THD_I over 40% at the connection point. The 11 kV medium-voltage network was simulated with 36 chargers, each at power level of 8.2 kV A, which makes it difficult to observe the total cancellation effect.

There is still a lack of studies focusing on clustering fast chargers and the impacts on both THD_I and THD_V (voltage total harmonic distortion) referring specifically to fast charging. It is critical to study the phase angles in order to understand how the amplitude of the harmonics measured will sum when considered part of a cluster (connected to the same feeder). The main goal of this study is to clarify the following questions: (i) investigate the voltage and current Total Harmonic Distortion (THD) caused by fast charging one single electric vehicle and standard limits compliance. (ii) how does the THD caused by fast charger/EV load vary along the charging cycle if at all?, and (iii) does the THD and TDD caused by charging two EVs simultaneously with the same fast charger decrease due to phase cancellation?

2. Theoretical background

Harmonic distortion is a deviation of the current or voltage waveform from a perfect sinusoidal shape. In the case of nonlinear loads, such as EV charge controllers, current distortion is very common due to the need of power electronics switches to convert power from AC to DC form. Introduction of these currents into the distribution system can distort the utility supply voltage and overload expensive electrical distribution equipment. In order to prevent harmonics from negatively affecting the utility supply, standards such as IEC 61000-3-12 [23]/2-4 [24] or IEEE Standard 519-1992 [25], were established with the goal of developing recommended practices and requirements for harmonic control in electrical power systems. These standards, widely adopted by the industrial and research communities, describe the problems that unmitigated harmonic current distortion may cause within electrical systems as well as the degree to which harmonics can be tolerated by a given system. Utilities are obliged to provide power quality whose limits among others depend on the level of voltage connection. End users on the other hand, are responsible for not degrading the voltage of the utility by drawing significant nonlinear or distorted currents. Power quality, specifically harmonic impact in Points of Common Coupling (PCC) is a subject of interest to both parties. The PCC with the consumer/utility interface is the closest point on the utility side of the customer's service where another utility customer is or could be supplied. The goal of applying the harmonic limits specified in the standards is to prevent one customer from causing harmonic distortions to another customer or the utility.