Renewable Energy, Environment, and Power Quality Journal (REE&PQJ)
ISSN:3020-531X
Volume No.2, July 2024

Analysis of the impact of Fast Electric Vehicle Charging Stations on Power Quality in Distribution Networks

João Pinto[1] and José Baptista[1,2]

[1] Department of Engineering
[2] INESCTEC UTAD Pole
University of Trás-os-Montes and Alto Douro
Quinta de Prados – Vila Real, 5001-801 Vila Real, Portugal

Abstract. One of the biggest obstacles when it comes to the electrification of the vehicle fleet is the charging time of an electric vehicle (EV), which means that users of these vehicles, when they need to charge their car, always look for fast charging stations. This is the charging method that has the shortest duration.
In the coming years, an increase in the proliferation of electric vehicles will lead to a greater demand for electricity, which in turn will put the distribution network to the test. Since the number of non-linear loads increases day by day, putting the distribution network under increasing stress, it is wise to study the effects of the high penetration of electric vehicles (EV) on the power quality of the network.
This paper aims to study the impact of charging EV on the quality of energy in the distribution network. First, an analysis of the harmonics and electronics (non-linear loads) associated with EV chargers will be done. Then, a simulation will be performed on the IEEE 33 network using the Matlab/Simulink simulation software.
Finally, a comparison will be made of the results obtained in the simulation and possible ways of mitigating the harmonics that non-linear loads inject into the electricity distribution network.

Keywords. Electrical Vehicle (EV), Harmonic Analysis, Matlab/Simulink, EV DC Fast Charger, Non-Linear Loads.

1. Introduction

The United Nations (UN) states that the global population has reached eight billion inhabitants. We have ceased to be a part of nature and have become apart from nature. After all these years, we need to reverse this transition. Our only option, once again, a more sustainable existence. We have an obligation to the living world to immediately halt, and preferably begin to reverse, the climate changes by addressing greenhouse gas emissions wherever they occur.
Since reducing emissions across all sectors is crucial to limiting global warming, road transportation is essential in achieving net-zero greenhouse gas emissions by 2050.
In 2017, road transportation accounted for 21% of the total carbon dioxide (CO_2) emissions in the European Union, the primary greenhouse gas. This percentage has been increasing over the past decades due to the significant reliance of the global economy on the transportation sector.
Passenger cars and light commercial vehicles are responsible for approximately 12% and 2.5% of the carbon dioxide (CO_2) emissions in the European Union (EU) [1].
On January 1, 2020, Regulation (EU) 2019/1242 came into effect, setting CO_2 reduction targets for cars and vans for the years 2020, 2025, 2030. This regulation also incorporates a mechanism to encourage the adoption of vehicles with zero and low emissions (ZLEV).
Heavy-duty vehicles – trucks and buses – are responsible for approximately a quarter of the CO_2 emissions from road transport in the EU and around 5% of the total EU emissions. Despite some improvements in fuel efficiency in recent years, these emissions are still on the rise due to the increased road freight traffic.
The EU aims to achieve climate neutrality by 2050, with an interim goal of at least a 55% reduction in greenhouse gas emissions by 2030.
Nowadays, three types of electric vehicles stand out, being encountered across various locations. These are known as Hybrid Electric Vehicles, Plug-in Hybrid Electric Vehicles (PHEV), and Full Electric Vehicles (FEV). Each of these vehicle types has distinct characteristics and varying impacts on their surrounding environment.
With the high penetration of EV in the automotive fleet, it is extremely necessary to understand the opportunities that arise and, in turn, the threats that also arise with this penetration, in order to eventually mitigate them [2] [3].
The development of the energy system over the years has resulted in the optimization of energy consumption. However, it is this sector that requires more attention, despite improvements in the efficiency of electronic equipment, energy consumption

continues to grow year by year. The electrical grid can pose significant problem, as it may not have the capacity to meet energy consumption needs or provide the required quality for modern equipment. The lack of power quality has been worsening due to the increasing use of non-linear loads and growing sensitivity of equipment to the quality of the supply voltage.

In [4] [5] the authors presented a different approach from the one that will be presented in this research, these authors focused on disturbing the voltage waveform profile. Others, such as in [6], chose to find the optimal location of EV charging stations (EVCS) in a distribution grid. There are other authors who have studied the topic of power quality, as in [7] [8] [9] [10].

In this paper, several EVCS operating simultaneously were simulated in a low-voltage network with different load profiles and different power levels. This was done in an attempt to identify the issues that these ECVS may bring to the IEEE 33 distribution network.

This paper is structured as follows. In Section II, is provided a brief overview of harmonics definitions and how to quantify them. Section III discuss electric vehicles charging methods and charging profiles. In Section IV the case studies are addressed, followed by Section V where the results will be presented. Finally, in Section VI, some conclusions are addressed.

2. Total Harmonic Distortion

In an ideal electrical system, the supply voltage must have constant amplitude, a sinusoidal waveform, constant frequency and symmetry in the case of three-phase systems. However, when some of the above-mentioned parameters are not verified, disturbances begin to appear in the electrical system. These disturbances affect the majority of loads downstream of the power grid, leading to malfunctions in devices connected to the power supply network [8]. The current and voltage waveforms should be purely sinusoidal, for which the current must be linearly related to the voltage. However, this relationship between voltage and current does not hold true when dealing with nonlinear loads, leading to disturbances. Currently, the EN 50160 standard [10] provides the recommended levels for the different power quality parameters [11]. One of these disturbances is called harmonic distortion. A non-linear load will consume a non-linear current, thus creating a disturbance in the current wave. This distortion in the voltage will cause a distortion in the electric current.

Before moving on to harmonic distortion, let's explain the Fourier series. The Fourier series states that all signals can be described as the sum of different signals.

$$\boldsymbol{y(t) = Y_0 + \sum_{n=1}^{\infty} Y_n \sqrt{sen(nwt + \psi_n)}} \qquad (\mathbf{1})$$

According to [2], the main harmonics components found in EVCS are those of order 5, 7, 11, 13, i.e. odd harmonics that are not multiples of 3, 6n±1, characteristic of three-phase AC/DC converters. High-order harmonics can be neglected because they have a very low amplitude. EV fast chargers are loads that drain high current values and therefore the amount of harmonics injected has a great impact on the power quality. For example, Tesla Supercharger (130 kW) charges the EV battery with a current around 217A [7].

The amount of harmonic distortion introduced into the distribution grid can be evaluated based in the total harmonic distortion (THD) and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency [5] [8] [12]. The IEEE 519-2022 standard [13] establishes the limits for voltage and current waveforms distortion that can exist in a distribution grid, as well as the waveform distortion limits [11]. However, the THD of a EVCS varies over the charging load factor, as the firing angles of the electronic equipment change in response to the various charging load factor depending on the state of charge (SOC) of the EV battery. According IEEE 519-2022, THD represents the ratio between the RMS value of the harmonics and the value of the fundamental component, and can be calculated based in equation 2, this denotes the current's THD.

$$\boldsymbol{THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1}} \qquad (\mathbf{2})$$

3. EV Charging Methods

Currently, alternating current charging stations is what occurs most frequently. The power for this charging stations comes directly from the distribution grid to the EV and converted to DC by the electronic converters located inside de vehicles. These converters are made up of two stages: 1st stage AC-DC, this stage is responsible for converting the AC current drawn from grid to DC current; 2nd stage DC-DC - converts the DC current to the reference levels of the EV's battery. This is known by Onboard charging that is found in all EVs, however it has some limitations in the rating power, as presented in [14]. When fast charging (offboard charging) is used, it also has the two stages mentioned above, but it doesn't have the rating power limitations that the vehicle can be charged with highs level currents around hundreds of Amperes. It should be emphasised that high charging currents reduce the life of the batteries, frequently use of this type of charging will damage the battery, and higher currents will cause greater losses.

Note that EV charging models are not constant over time. EV batteries have a built-in management system - BMS - which is responsible for managing the battery, depending on the battery's SOC. The battery behaves differently when charging and discharging, for example if we are dealing with vehicles that inject current into the distribution network (V2G) [15].

A. State of Charge (SOC)

The battery state of charge is probably the most important parameter in the BMS, as it represents the ratio between the capacity currently available in the battery and the rated capacity, as shown in equation 3.

$$\boldsymbol{SOC = \frac{Available\ Capacity}{Rated\ Capacity}} \qquad (\mathbf{3})$$

A common method for estimating a battery's SOC uses the charging current to calculate the capacity drawn in the time period corresponding to that profile. Equation 4 describes this method, where only the battery's available capacity is taken into account [3].

$$\boldsymbol{SOC = SOC_{initial} - \int \frac{i_{load}}{C_{available}} dt} \qquad (\mathbf{4})$$

It is important to emphasise that the SOC is a dynamic measure, i.e. it changes continuously as the battery is charged and discharged. In addition, the real capacity of a battery can decrease over its lifetime due to ageing.

B. Electric Vehicle Battery Charging Characteristics

The charging characteristic of a battery has several distinct phases. In the first phase, when the battery is discharged the charging current is maximum. The SOC increases rapidly at the start of the charging process. In the intermediate phase, the charging current is reduced to avoid overcharging. In this phase, the SOC continues to increase, but at a slower rate. Finally, when the SOC approaches 100%, the current is further reduced to prevent damage to the battery caused by overcharging.
For this study, only lithium-ion batteries were considered, as lithium-ion batteries can be found in today's car fleet [16]. Tesla is one of the main car brands using these batteries, and another example is the popular Nissan Leaf.
The typical charging profile of a lithium-ion battery is show in Figure 1. For an SOC around 20% the battery will charge at rating power, as it approaches a SOC of 80% the charging power will decrease. This is done in an attempt to maintain the battery's integrity.

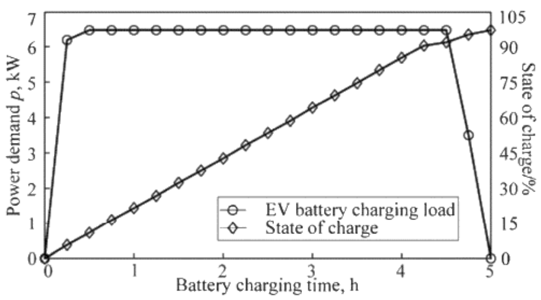

Fig.1. Charging Profile of a Lithium-ion battery

4. Case Study

In this research, several EVCS operating in a low-voltage grid with different load profiles and different power levels was simulated. This was done in an attempt to identify the issues that these ECVS may bring to the distribution network.
This study uses Matlab/Simulink to develop the simulation model. Simulink is an extension of Matlab that offers a graphical platform for the simulation and analysis of dynamic systems, allowing the construction of block diagrams that represent the behaviour of a system and simulate performance over time.

A. Distribution Network – IEEE 33

The network used in the case study was the IEEE 33-bus network shown in Figure 2. The IEEE 33 network is a low-voltage electrical distribution system consisting of 33 busbars, 32 lines and several loads. This network is often used as a test model for a wide set of case studies. The IEEE 33 network is a simplified system that does not represent all the characteristics of a real distribution system, but it is widely used as a test model to evaluate different technologies behaviour. The total active power of this distribution network is 3715 kW, and the total reactive power is 2300 kVar, with base power values of 100 MVA and a base voltage of 12.66 kV. Without EVCS, the grid has an active power loss of 176.367 kW and a reactive power loss of 117.43 kVar. The load values associated with this network, as well as the resistance and reactance values of the branch lines, can be found in [17].

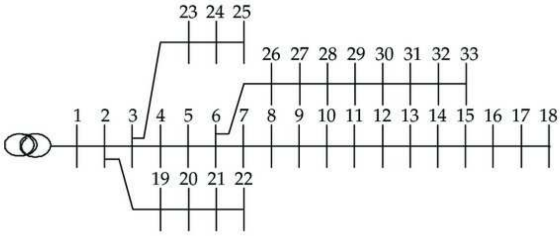

Fig.2. IEEE 33 bus network

B. Charging Station Model

EV fast charging stations typically employ high-power three-phase AC/DC converters to quickly charge the batteries of EV. The use of three-phase converters in these stations allows for more efficient power distribution, reducing the load on each phase and enabling higher power levels. This is crucial for achieving faster charging times, a key factor in promoting the widespread adoption of EV. In this study, a model of a three-phase AC/DC EVCS was designed using MATLAB/Simulink, as shown in Figure 3.

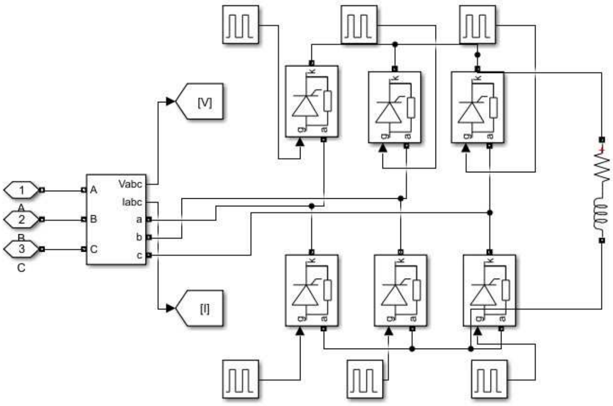

Fig.3. Model of an Electric Vehicle Charging Station used in Matlab/Simulink

C. THD Calculation

As explained above, harmonic distortion occurs when there are changes in the voltage or current waveforms. Total Harmonic Distortion (THD) is a parameter used to measure the harmonic content in an electrical system. It quantifies the deviation of a waveform from its ideal sinusoidal shape by considering the presence of harmonic frequencies. Total Harmonic Distortion is an important parameter in all electrical systems, since the presence of distortions in the electrical signal can cause several issues, such as reduced energy efficiency, overheating of equipment (increased losses), interference with other electrical equipment and resonances. Monitoring and controlling THD are essential in power systems, especially in sensitive environments. Regular measurements of THD help identify and address harmonic issues to maintain a stable and reliable power supply.

D. Studied Scenarios

In this study, a maximum number of six EVCS connected at different points on the network will be considered. A genetic algorithm taken from [18] was used to choose the ideal location for the charging points.

Table I. – Location of EV Charging Stations

Number of EVCS	**Busbar Location**	**Lower voltage (p.u.)**
6	2,5,8,19,22,23	0.90005

The location chosen for the EVCS took into account the maximum voltage grid deviations allowed and the stations were dispersed throughout the network, in an attempt to satisfy the largest number of customers.

5. Results and Discussion

To better understand the impact that the EVCS can have in the grid, different simulation scenarios were tacked into account, considering different EV battery state-of-charge. In the first scenario, a SOC of 20% was considered, that is, with the EV battery almost discharged. An analysis was then carried out at the level of harmonic distortion caused at different points in the grid.

Thus, in a low level SOC situations, it will be possible to assess the voltage and current waveforms circulating in the grid, since a low SOC levels will require high current charging ratings. Figure 4 shows the EVCS location considered for the first scenario.

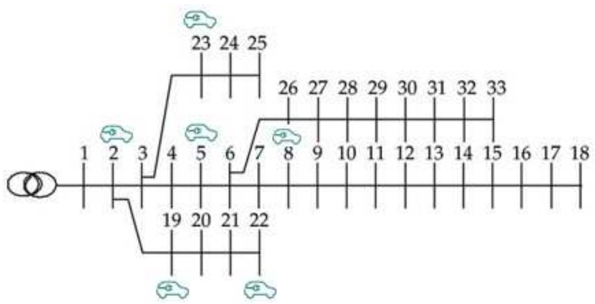

Fig.4. Location of Electric Vehicle Charging Stations

The use of fast chargers will lead to high current demands on the grid, in the order of hundreds of Amperes. For all the simulation, carry out no filters were used, meaning that in the absence of such equipment, harmonics generated during EV charging phase will be injected into the distribution network, leading to high THD levels. Figure 5 show the voltage and current harmonic levels at the selected connection EVCS busbars. By analyzing figure 5, it can be seen that the THD values obtained for current and voltage are very high, with the THDv values being above the limits recommended by the EN 50160 standard.

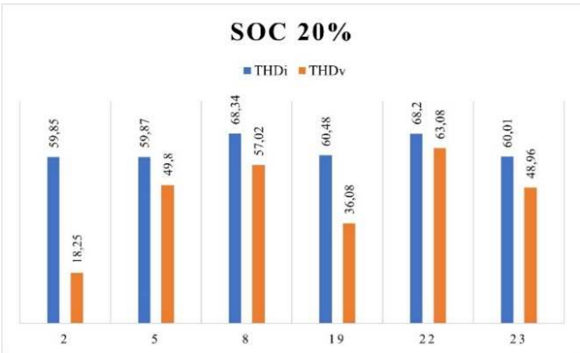

Fig.5. THDi and THDv for a SOC of 20%

As stated above, lithium-ion batteries have a non-linear behaviour, which means that the charging rate decreases as the SOC approaches 100%, as shown in Figure 1. Figure 6 and figure 7 shows the current and voltage waveforms for node 22.

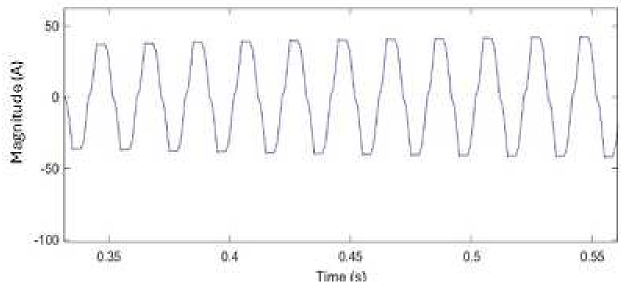

Fig.6. Current waveform on busbar 22

In a second scenario, an EV battery SOC of 80% was considered, in this scenario the EVCS input power levels are lowers and consequently the charging currents decrease. Figure 8 show the voltage and current harmonic levels for this scenario. As can be seen, the current harmonic distortion remains high but the voltage harmonic distortion are significantly lower in this scenario. Figure 9 and Figure 10 shows the harmonic spectrum for current and voltage respectively, at busbar 2.

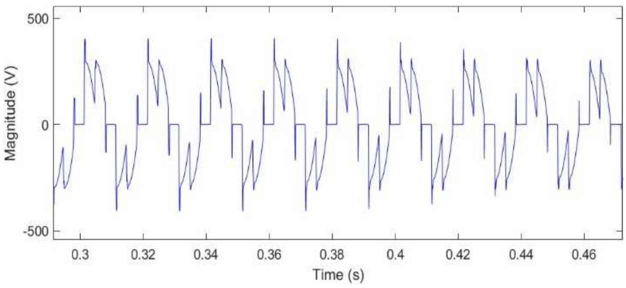

Fig.7. Voltage waveform on busbar 22

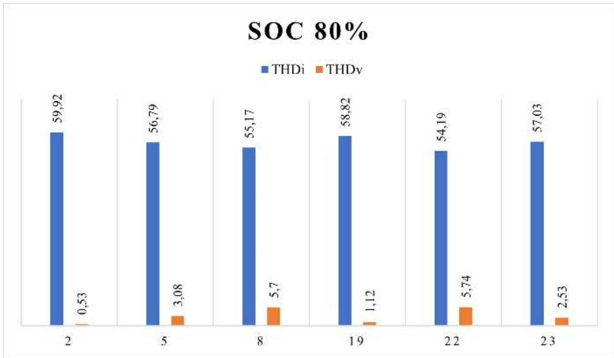

Fig.8. THDi and THDv for a EV SOC of 80%

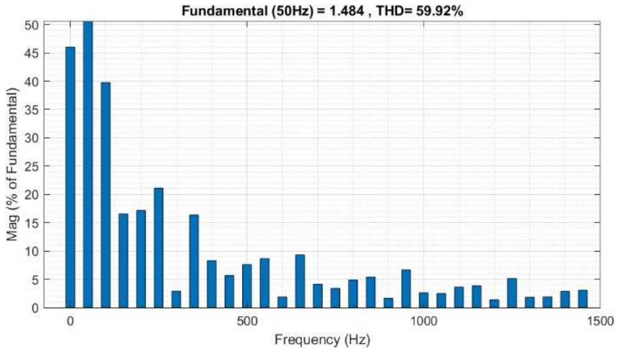

Fig.9. Harmonic Spectrum of current at busbar 2, for a EV SCO of 80%.

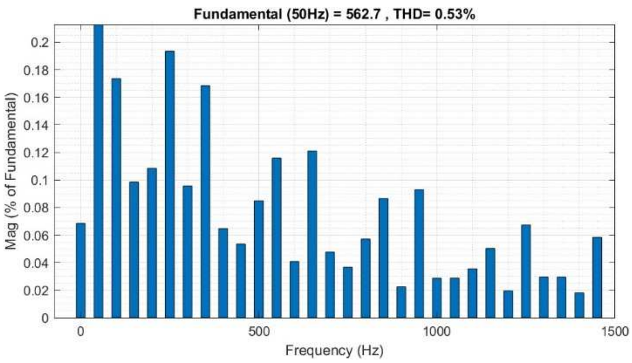

Fig.10. Harmonic Spectrum of voltage at busbar 2, for a EV SCO of 80%.

It is important to emphasise that harmonics can have a significant impact on the power factor of an electrical system. The presence of harmonics increases the reactive power in the system, thus reducing the power factor. This is due because harmonics introduce additional reactive currents that do not contribute directly to the active power. Therefore, the effective power factor of a system with harmonics will be lower than the power factor without harmonics.

In the next simulation scenario, the network will be simulated with only two EVCS, connected in bus 2 and bus 19, as shown in figure 11. In this scenario, an analysis was conducted in order to evaluate the stability of the system, taking into account the presence and position of these two EVCS.

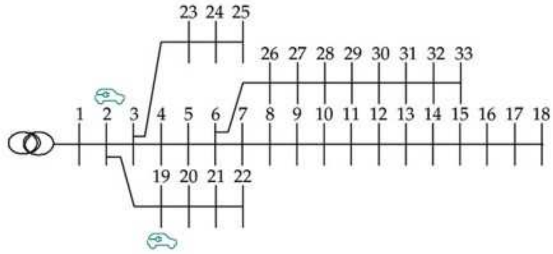

Fig.11. Location of Electric Vehicle Charging Stations

The graph of figure 12 shows that the disturbances resulting from the simultaneous use of the two EVCS in these two nodes will be propagated along the 33 busbars of the network, significantly affecting the current and voltage waveforms as shown in figure 13 and figure 14 respectively.

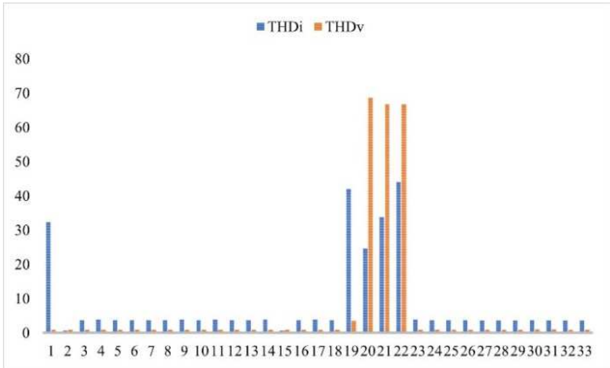

Fig.12. THDi and THDv along the IEEE 33 network for the case study of two EVCS.

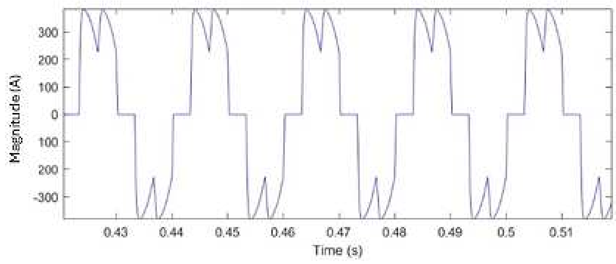

Fig.13. Current waveform on busbar 2

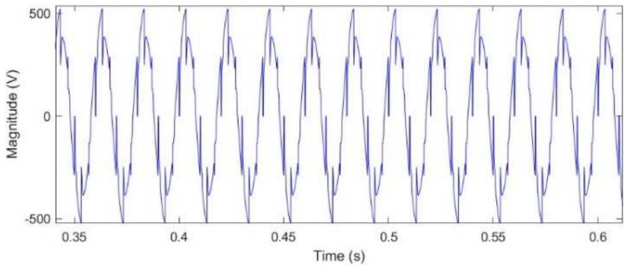

Fig.14. Voltage waveform on busbar 2

With these simulations it was possible to verify the enormous impact that EVCS have on distribution networks, showing the lack of capacity of these infrastructures to accommodate a high number of loads of this type.

While fast chargers offer the advantage of recharging an EV's battery in a short time, they require high powers levels that can overload existing electrical infrastructures.

6. Conclusions

This study evaluated the impact that EV fast chargers have on power quality, particularly with regard to voltage and current waveform and harmonic distortion levels. To carry out this study, a Simulink model capable of simulating the behaviour of EV fast chargers was developed, and three different study scenarios were considered.

The results show that for the first case study, the network cannot support the six EVCS operating simultaneously because the power levels involved are very high resulting in high levels of harmonic distortion levels for current and voltage. Another conclusion that can be drawn is the fact that the distortion levels result in values above those allowed by standard EN50160. In the second scenario, the EVCS were designed to operate at lower power levels, which resulted in lowers harmonic distortion levels for current and voltage when compared to the first scenario, however, the current waveform remains very distorted.

Finally, the study of the third scenario resulted in lower harmonic distortion levels, but it should be emphasised that the disturbances caused by the ECVEs in all studied scenarios will affect all of the distribution network.

The level of integration of new EVCS connected to distribution networks will continue to increase in the future. Studies like this one help to predict the impacts that these additional loads may have on the electrical distribution grids. When there is knowledge of these topics at an early stage of planning, it will be easier to identify and mitigate the negative impacts that these loads have on the distribution networks. The implementation of suitable filters can minimize the impact that these loads have on the distribution network, allowing an increase in the number of ECVS made available to electric vehicle owners.

Acknowledgement

This work is financed by National Funds through the Portuguese funding agency, FCT - Fundação para a Ciência e a Tecnologia, within project LA/P/0063/2020.
DOI 10.54499/LA/P/0063/2020 https://doi.org/10.54499/LA/P/0063/2020

References

[1] Agência Portuguesa do Ambiente (APA), https://apambiente.pt/clima/transporte-rodoviario (acessed on 21/02/2023), 2022.
[2] L. Zhang and J. Liu, “Research on harmonic of electric vehicle charger based on Matlab” Ph.D thesis, Horth Chine Electric Power University Beijing, China, 2013.
[3] Y. Xu, Y. Xu, Z. Chen, F. Peng and M. Beshir, "Harmonic analysis of electric vehicle loadings on distribution system”, 2014 IEEE International Conference on Control Science and Systems Engineering, Yantai, China, 2014, pp. 145-150. Doi: 10.1109/CCSSE.2014.7224526.
[4] Lucas, Alexandre & Fausto, Bonavitacola & Kotsakis, Evangelos & Fulli, Gianluca. (2015). “An experimental approach for assessing the harmonic impact of fast charging electric vehicles on the distribution systems”.
[5] Olcay, K.; Çetinkaya, N. “Analysis of the Electric Vehicle Charging Stations Effects on the Electricity Network with Artificial Neural Network”. Energies 2023, 16, 1282. Doi: 10.3390/en16031282
[6] M. A. Bucarelli, A. Geri, M. Maccioni, F. M. Gatta, T. Bragatto and M. Paulucci, "Impact of ultrafast EV charging stations on the electrical distribution grid: a case study in Terni”, 2023 IEEE International Conference on Environment and Electrical Engineering (EEEIC / I&CPS Europe), Madrid, Spain, 2023, pp. 1-6. Doi: 10.1109/EEEIC/ICPSEurope57605.2023.10194699.
[7] A. Supponen, A. Rautiainen, J. Markkula, A. Mäkinen, P. Järventausta and S. Repo, "Power quality in distribution networks with electric vehicle charging - a research methodology based on field tests and real data”, 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER), Monte Carlo, Monaco, 2016, pp. 1-11. Doi: 10.1109/EVER.2016.7476376.
[8] A. Lucas, Fausto Bonavitacola, Evangelos Kotsakis, Gianluca Fulli, “Grid harmonic impact of multiple electric vehicle fast charging, Electric Power Systems Research”, Volume 127, 2015, Pages 13-21. Doi: 10.1016/j.epsr.2015.05.012.
[9] M. Basu, E. D. Coyle, and K.Gaughan“Harmonic distortion caused by EV battery chargers in the distribution systems network and its remedy”. 39th International Universities Power Engineering Conference, UPEC 2004 - Conference Proceedings. 2. 869 - 873 vol. 1. 10.1109/UPEC.2004.192471.
[10] EN 50160. “Voltage characteristics of electricity supplied by public distribution systems”, Brussels, EN 50160-CENELEC 1994, 2010 (Revised).
[11] Lucas, A., “Fast charging diversity impact on total harmonic distortion due to phase cancellation effect” – Fast charger's testing experimental results, EC-JCR, Publications Office, 2017
[12] V. -L. Nguyen, T. Tran-Quoc and S. Bacha, "Harmonic distortion mitigation for electric vehicle fast charging systems”, 2013 IEEE Grenoble Conference, Grenoble, France, 2013, pp. 1-6. Doi: 10.1109/PTC.2013.6652435.
[13] IEEE Standard 519-2022, IEEE Standard for Harmonic Control in Electric Power Systems
https://powerquality.blog/2022/12/02/ieeestandard-519-2022- update-and-changes-from-prior-version-2014/ (acessed on 11/04/2023), 2022.
[14] Woodman, Nicole & Bass, Robert & Donnelly, Mike. 2018. “Modeling Harmonic Impacts of Electric Vehicle Chargers on Distribution Networks”, pp.2774-2781. Doi:10.1109/ECCE.2018.8558207.
[15] U. C. Chukwu, "The Impact of V2G Placement on a Feeder Line”, 2020 Southeast Con, Raleigh, NC, USA, 2020, pp. 1-2. Doi: 10.1109/SoutheastCon44009.2020.9249723.
[16] K. Qian, C. Zhou, M. Allan and Y. Yuan, "Load model for prediction of electric vehicle charging demand”, 2010 International Conference on Power System Technology, Zhejiang, China, 2010, pp. 1-6. Doi: 10.1109/POWERCON.2010.5666587.
[17] Wazir, A., Arbab, N.: Analysis and optimization of IEEE 33 bus radial distributed system using optimization algorithm. J. Emerg. Trends Appl. Eng. 1(2), 17–21, 2016.
[18] E. Gomes, A. Cerveira , and J. Baptista, “Optimal Location of Electric Vehicle Charging Stations in Distribution Grids Using Genetic Algorithms” OL2A, 2023. Doi:10.1007/978-3-031-53025-8_38.