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Article

Harmonic Distortion and Hosting Capacity in Electrical Distribution Systems with High Photovoltaic Penetration: The Impact of Electric Vehicles

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Abstract: Electric vehicles and the charging stations and their operation require a thorough examination to evaluate the effects on the electrical network. This becomes particularly challenging in the case of high photovoltaic penetration, due to the variability of the solar resource and vehicle connection patterns, which cater to individual user preferences. The current study investigates the impact of harmonics generated by charging stations and electric vehicles on different photovoltaic penetration scenarios within an electrical distribution system. DC and AC charging stations are analyzed. The findings reveal a third harmonic magnitude increase exceeding 300% compared to other cases. Furthermore, this study demonstrates the effects of current and voltage variations on end-users and substation transformers. The impact of harmonics on the hosting capacity of the network is also analyzed, resulting in a 37.5% reduction in the number of vehicles.

Keywords: electric vehicle; charging stations; photovoltaic generation; distribution system; harmonics

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1. Introduction

Over the past 5 years, there has been significant growth in the adoption of electric vehicles (EVs). However, integrating EVs into electrical distribution systems involves a thorough examination of their impact on the electrical network. The connection of EVs to the power grid may cause an elevation in voltage and current harmonic distortion, as well as a decrease in the lifespan of distribution transformers due to elevated temperatures [1]. In addition, harmonic distortion can also arise from the inverters of grid-connected photovoltaic (PV) systems, with some harmonics reaching high levels [2]. The integration of EVs with a high penetration of PV systems can create challenges for electrical distribution grids. Additionally, a large quantity of electric vehicles may result in power quality issues, such as service interruptions, fluctuations in voltage and current, and harmonic distortion [3]. Hence, it is crucial to carefully plan the integration of electric vehicles into PV-dependent systems to prevent any undesirable disruptions to the distribution system.

Several studies have investigated the influence of EVs on electrical distribution systems, analyzing both EV penetration and PV systems [3–7]. However, there are only a few case studies that investigate the integration of these technologies in electrical grids with a high concentration of PV systems. It has been demonstrated that the presence of EVs in the electrical grid has an impact on total harmonic distortion (THD). In [8], the effect of level two fast chargers on the grid was investigated. As the penetration of EVs on a feeder rises, the degree of harmonic distortion also rises, as observed. Furthermore, the study investigated the impact of the electric vehicle supply equipment (EVSE)'s location on the feeder. The outcomes indicated that the highest THD value was at the end of the feeder, and the voltage at the user's terminals decreased when the EVSE was located further from the feeder's origin. These findings have significant implications for the deployment of EV charging infrastructure in the power grid, as careful EVSE placement can mitigate the negative effects of EVs on harmonic distortion. Moreover, these findings emphasize the necessity for additional research on the influence of EVs on the electrical grid and the development of strategies to guarantee the dependable and effective integration of electric vehicles into the grid.

It has also been observed that the individual harmonic distortion caused by EVs limits the capacity of the electrical grid. In a study conducted by the authors in [9], a sensitivity analysis of models with uncertainty in medium voltage networks was assessed. The results showed that individual harmonics cause a decrease in the hosting capacity due to the probability of exceeding technical limits by approximately 67%. These findings underscore the need for careful consideration of the impact of EVs on the electrical grid and the potential limitations that may arise. It is essential to ensure the reliability and efficiency of the electrical grid as EV adoption continues to increase. Further research on the impact of EVs on the electrical grid's hosting capacity and the development of strategies to mitigate the negative effects of harmonic distortion will be crucial in facilitating the integration of EVs into the electrical grid.

This study focuses on investigating the harmonic effects of EV charging stations in an electrical distribution grid with high PV penetration, considering both peak and valley demand. To determine the actual harmonic values, the power quality of fast-charging stations employing direct current (DC) and slow-charging stations using alternating current (AC) for KIA- and BYD-brand vehicles was measured. Subsequently, the system was simulated utilizing OpenDSS, and validation was carried out using the IEEE European low-voltage test feeder case.

The current study is an extension of the article titled "Harmonic Impact of Electric Vehicles in Electrical Distribution Systems with High Photovoltaic Penetration", presented at the V Ibero-American Congress of Smart Cities.

This article's key contributions include (a) a comprehensive analysis and assessment of the impact and distinct levels of harmonics on the behavior of distribution systems with high PV penetration and EV loads, proposing that a high penetration of photovoltaic generators and EVs has a direct relationship with amplified harmonics and (b) indicating that THD effects on voltage values at loads are significant and must be considered.

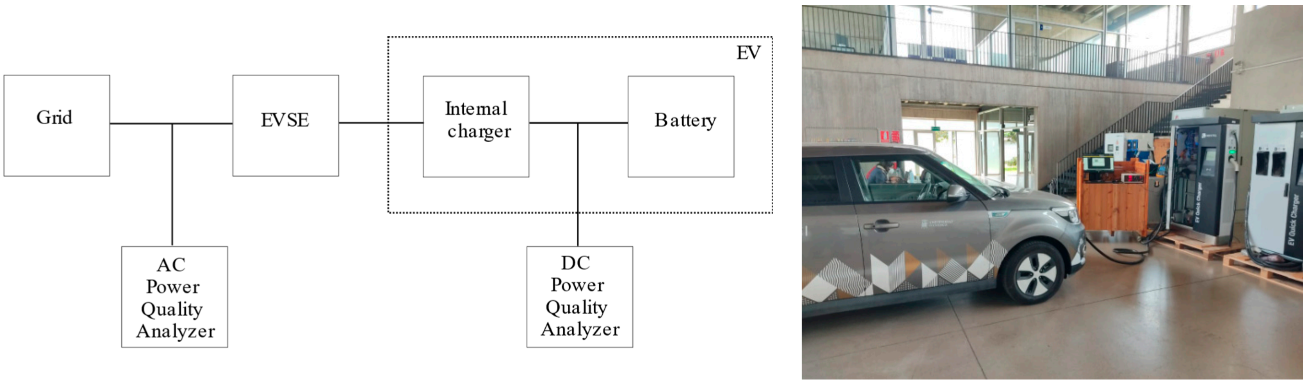
2. Methodology

The electrical parameters for this study were acquired by measuring two EV brands and charging stations under real charging conditions. Furthermore, the charging stations and electric vehicles were modeled as both storage components and sources of harmonic generation. The specific modeling of EVs as storage components was deemed necessary due to the standard model available in OpenDSS, which permits the configuration of various efficiency parameters, including state of charge or discharge and power control. However, as there is no specific model designed for EVs, MATLAB must be employed to control their operations. In contrast, the standard OpenDSS model was deemed sufficient for modeling PV systems, enabling the incorporation of a wide range of parameters, including irradiance, efficiency, and temperature effects. Lastly, a standard electrical IEEE standard case study was utilized to conduct the simulations.

2.1. Charging Stations and Electric Vehicles

Tests were carried out at the University of Cuenca's laboratory [10], using a Fluke 435 II power quality analyzer, to gather real data on current harmonics. The measurements were conducted on a BYD T3 and Kia Soul EVs, as well as on a 7.2 kW AeroVironment

RS 25 AC electric vehicle supply equipment (EVSE) (sourced from California, USA) and a 50 kW Circontrol Raption 50 model (sourced from Barcelona, Spain) fast DC EVSE (refer to Figure 1).



(**a**) (**b**)

Figure 1. Measurement equipment: (**a**) connection diagram; (**b**) EV and EVSE.

The laboratory measurements of voltage harmonics, encompassing both magnitude and angle, yielded the results that are shown in Table 1. Additionally, the values obtained from prior studies available in the literature involving other models of EVs have also been included. Table 1 shows the results of the laboratory measurements up to the eleventh harmonic for the parameters (param) in magnitude and phase angle of voltage. It presents the harmonics generated by an electric vehicle charger (EV charger), a Nissan Leaf vehicle, a BYD-brand vehicle with an alternating current charging station (BYD AC) and direct current (BYD DC), as well as a Kia-brand vehicle, likewise with an alternating current charging station (Kia AC) and a direct current one (Kia DC).

Table 1. Harmonics magnitude and angles obtained from measurements and other studies.

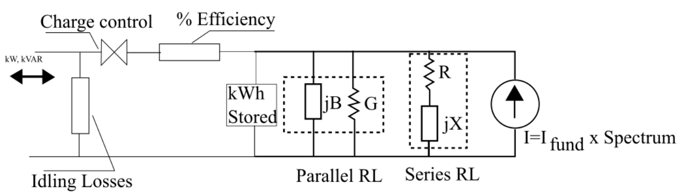
No.	Param	EV Charger [6]	Nissan Leaf [5]	BYD AC	Kia AC	BYD DC	Kia DC
1	Mag.	100	100	100	100	100	100
	Angle	−55	−26	136	143	8.6	28.6
3	Mag.	9.20	25.00	9.91	6.31	2.40	6.22
	Angle	120.00	−94.00	98.00	102.00	6.50	32.00
5	Mag.	62.20	17.00	8.47	1.15	1.73	14.55
	Angle	255.00	−96.00	120.00	131.00	7.20	36.00
7	Mag.	41.80	14.20	8.11	0.83	2.14	5.61
	Angle	−28.00	−72.00	146.00	153.00	6.80	31.00
9	Mag.	1.48	9.69	7.30	0.49	1.13	4.34
	Angle	−3.00	−68.00	152.00	161.00	5.70	34.00
11	Mag.	7.08	5.04	6.92	0.64	2.45	5.06
	Angle	−2.00	−49.00	168.00	182.00	5.60	35.00
Charge Efficiency		-	-	92.90%	89.80%	94.60%	91.70%

Additionally, measurements were carried out to evaluate the efficiency of both the charging station and the internal converter of the vehicle. The performance of an EVSE was assessed using instrumentation to ensure accurate measurements. An AC power quality analyzer Fluke 435 II was utilized at the input of the station to monitor critical electrical parameters, such as the current, voltage, and harmonics in both magnitude and angle.

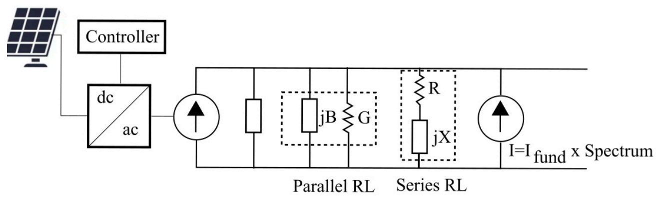
Furthermore, a Hioki PW3337 DC (sourced from Nagano, Japan) power quality analyzer was connected to the internal charger circuit and the EV battery to obtain the charging efficiency. The charging processes of EVs were tested from a state of charge (SOC) of 10% to 95% to ensure a comprehensive analysis of charging performance. The experiment was conducted in the University of Cuenca's laboratory. The efficiency of EVSEs was examined in both AC and DC charging modes, with the highest efficiency observed during DC charging at 94.6%, while the lowest efficiency was recorded during AC charging at 89.8%.

2.2. Simulation Characteristics

OpenDSS was utilized for simulation purposes, wherein EVs were represented as storage elements and were dispersed across different phases of the system, while also acting as a source of harmonics. The simulation process involved the use of two distinct models, one for the EV and another for the PV. The EV was accurately modeled as a battery with a charge controller, customizable efficiency settings, and a current source to generate harmonic waves. The model employed consists of a battery storage element connected to each load bus of the system. It utilizes a two-phase model, with each phase operating at 230 VAC and a power factor of 1. The specific spectrum and load curve for the model can be found in the study's repository, specifically in the Input_data/circuit/autos folder. Similarly, the PV system was designed to operate with a DC-to-AC converter, which served as the control signal for a harmonic current source. Standard values were employed for efficiency, temperature, and irradiation to ensure consistency throughout the simulation process (see Figure 2). The PV system in OpenDSS is defined as a PVSystem element, connected to the system buses according to each scenario. It is configured as a single-phase system operating at 230 VAC and an operating temperature of 25 °C. Additionally, the irradiation, efficiency, harmonic spectrum, and power–temperature adjustment curve are defined in the repository files, specifically in the Input_data/circuit/fotovoltaico folder.



(**a**)



(**b**)

Figure 2. Simulation models. (**a**) Electric Vehicle. (**b**) PV generator.

The models employed for the EV and PV generator incorporate series and parallel impedances, specifically series RL and parallel RL. To accurately align with the power profile, OpenDSS computes the values of conductance (G), susceptance (jB), and impedance (R+jX) for both the vehicle's power consumption and the generator's power generation requirements according to its power delivery requirements. Regarding the harmonic spectrum, the harmonic values obtained from Table 1 are applied to EVs, whereas default values from OpenDSS are utilized for PV generators. Furthermore, the efficiencies (% efficiency) indicated in Table 1 are incorporated into the EV model, and ideal idling losses are assumed.

This approach enables the accurate modeling and analysis of harmonics impact of EVs and PV systems. A critical consideration during the simulation process was the connection time of EVs, which could significantly impact the results of the analysis. To precisely reflect the behavior of EV connections, a multimodal probability distribution function (PDF) was employed. Such a PDF accounts for multiple modes or peaks that demonstrate the connection of electric vehicles at various times of the day. For residential EVSEs, it is worth noting that, while the connection can be established at any point during the day, the maximum modes transpire at 08:00 and 18:00. These timeframes coincide with when users typically return home with their EVs and proceed to connect them for charging purposes [11]. The function used was designed with modes at 02:00, 08:00, and 19:00, and standard deviations of 2 h, to generate a realistic representation of EV connection behaviors (see Figure 3). In the simulation, EVs maintain a charging regimen lasting between 6 and 8 h, reaching a SOC ranging from 80% to 100%. This encompasses up to 55 distinct charging behaviors, depending on the specific scenario being analyzed. The OpenDSS file utilized to describe the charging duration, as well as the connection and disconnection times, can be downloaded from the repository associated with this study. It is located within the Input_data/circuit/autos folder.

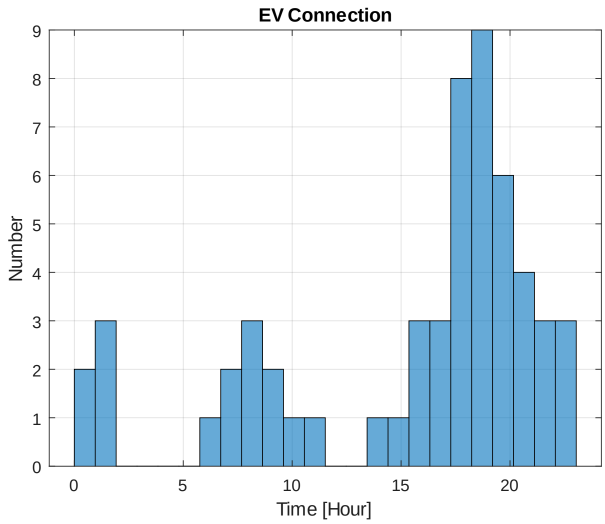


Figure 3. Electric vehicle connection probability distribution function used in simulation.

To automate the simulation process in OpenDSS, MATLAB was employed as a tool for controlling the timing of both customer load profiles and EV connections. The integration of MATLAB with OpenDSS allowed for a streamlined and efficient simulation process, which ultimately facilitated the accurate analysis of the performance of EVSEs.

2.3. Application Scenarios

To evaluate the impact of harmonics, a simulation was conducted utilizing the IEEE European low-voltage test feeder model. Three scenarios were analyzed based on the PV generation location: (1) 14 distributed PV systems with a capacity of 5 kW each and 14 EVSEs with a capacity of 7.2 kW each; (2) a central PV system with a capacity of 70 kW and 14 EVSEs with a capacity of 7.2 kW each, as illustrated in Figure 4; and (3) PV and EV distributed across all loads. The harmonic spectrum from Table 1 was assigned randomly to each scenario, while for the PV generators, the harmonic spectrum from [12] was employed. A clear sky irradiance profile was applied to the PV systems. The study examined the following scenarios:

- The initial test case solely examines residential loads within the system, devoid of EVs or PVs (Case 1).
- EVs connected without PV generation and without harmonic effects (Case 2).
- EVs connected with distributed PV generation and without harmonic effects (Case 3).
- EVs connected with single PV generation and without harmonic effects (Case 4).
- EVs and PV generation distributed across the loads without harmonic effects (Case 5).
- EVs connected without distributed PV generation and with harmonic effects (Case 6).
- EVs connected with distributed PV generation and with harmonic effects (Case 7).
- EVs connected with single PV generation and with harmonic effects (Case 8).
- EVs and PV generation distributed across the loads with harmonic effects (Case 9).

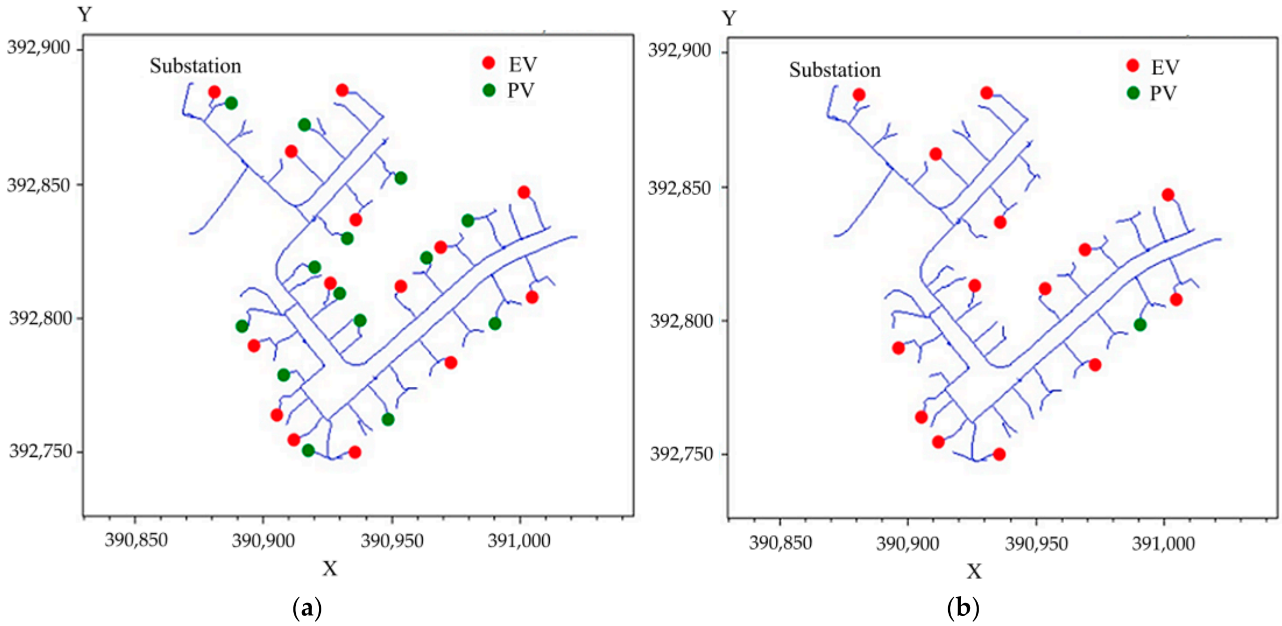


Figure 4. Test cases analyzed: (**a**) distributed EV and distributed PV systems; (**b**) distributed EV and single PV system.

The analysis focused on observing the impact on the substation response, the maximum total harmonic distortion (THD), and the voltage and current at the client terminals.

3. Results

During the simulation, the power rating of the transformer in the substation, as well as the highest and lowest voltages recorded across the loads, were taken into account. Moreover, the maximum THD in the loads was also considered.

3.1. Power of the Substation Transformer

Initially, the power of the substation transformer was analyzed for the scenarios outlined in Section 2.3. Figure 5 illustrates that the power of the substation transformer fluctuates as EVs are introduced into the network and the impact of harmonics caused by the EVs is taken into consideration. Case 2 without harmonics exhibits the lowest power value, whereas the highest power value among all scenarios is observed when harmonics are introduced into the network. The high current resulting from harmonics saturates the system's conductors, which diminishes the effect of power injection by the PV generation. Additionally, the situation deteriorates when there is only one PV generation in the distribution system. Likewise, an analysis of the network's performance in Cases 5 and 9, which include distributed PV and EV systems, reveals a distinct impact of harmonic distortions. Specifically, the presence of harmonics causes a reduction in the current output of the PV systems.

The power with harmonics is internally calculated by OpenDSS through multiple simultaneous simulations. First, the power of the fundamental component is computed, followed by repeated simulations for each of the harmonic components configured in the spectrum file. Consequently, OpenDSS provides separate power results for each harmonic, and in MATLAB, the contribution of each harmonic is summed. Equation (1) illustrates the outcome of this calculation.

$$P = \sum_{n=1}^{m} \frac{V_n I_n}{2} \cos(\theta_n - \varphi_n) \tag{1}$$

where:

P is the active power;

n is the harmonic;
V_n is the voltage of nth harmonic;
I_n is the current of nth harmonic;
θ_n is the voltage angle of nth harmonic;
φ_n is the current angle of nth harmonic.

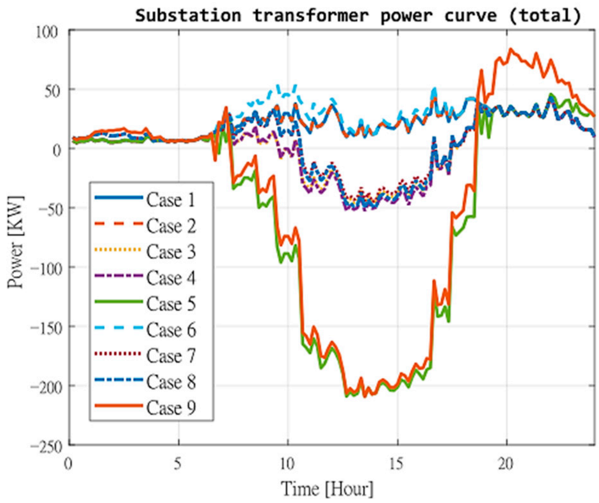
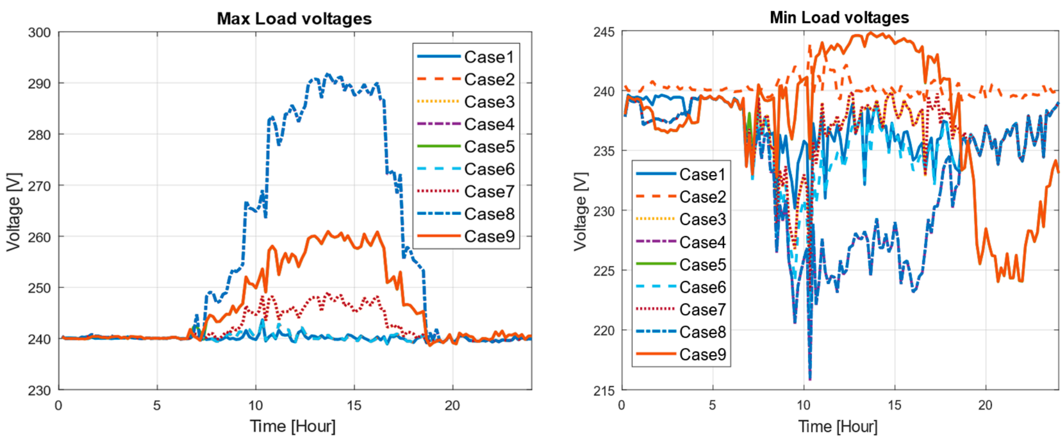


Figure 5. Substation transformer power curve for each case.

3.2. Load Voltages

This study examined the behavior of maximum and minimum voltages across the loads (customers) in the network to ensure that they meet the limit values prescribed by the ANSI C84.1-2006 standard for each simulation scenario. A base RMS voltage of 240 VAC was assumed for the network, and the standard limits of 0.9 pu and 1.05 pu were used, which correspond to 216 VAC and 252 VAC, respectively. The simulations showed that Cases 5 and 9 had lower RMS voltage values than case 8, which had the highest voltage at the customer terminal connected to the PV generator. It was observed that high voltage values coincided across different simulation cases (see Figure 6). Notably, minimum voltage values were found to be within the standard limits across all simulation scenarios.



(**a**) (**b**)

Figure 6. Voltages at customer bars. (**a**) Maximum values on all customers by selected case. (**b**) Minimum values on all customers by selected case.

Table 2 displays the highest and lowest power values of the substation transformer, along with the voltage and current at the customer's terminals. It is evident that in Case 2 with harmonics, the transformer requires the most power, both in terms of maximum and minimum power during the 24 h period. With regard to voltage, scenarios with harmonics do not seem to have a significant impact. However, the current remains at a high level during the minimum of Case 2 with harmonics.

Table 2. Power, current, and voltage obtained from the analyzed scenarios.

Case		Transformer Power (kW)	Load Voltage (V)
(1) Base	Max	48.95	243.67
	Min	4.81	225.50
(2) Only EVs	Max	48.95	243.99
	Min	4.81	238.89
(3) EV and distributed PV	Max	43.29	249.01
	Min	−47.06	223.07
(4) EV and single PV	Max	43.29	291.93
	Min	−52.75	215.76
(5) Distributed EV and distributed PV	Max	45.76	260.91
	Min	−209.20	224.01
(6) Case 2 plus harmonics	Max	54.48	244.02
	Min	5.79	221.02
(7) Case 3 plus harmonics	Max	43.29	249.02
	Min	−44.94	223.23
(8) Case 4 plus harmonics	Max	43.29	291.97
	Min	−50.28	215.95
(9) Case 5 plus harmonics	Max	83.81	260.94
	Min	−209.20	224.04

3.3. Load Harmonics

Through a comprehensive analysis of the system's response to specific injected harmonics throughout a 24 h duration in each case, notable observations were made. The findings revealed that the third harmonic held a dominant presence, aligning with the measurements conducted in controlled laboratory settings. The obtained results exhibit distinct harmonic profiles for Case 6 and Case 7, showcasing interesting trends in the magnitudes of various harmonics. In Case 6, the analysis unveiled a maximum value of 2.5% for the third harmonic, indicating its prominent influence on the system. On the other hand, the seventh harmonic exhibited the lowest magnitude, with a minimum value of 0.3%. Case 7 demonstrated a similar pattern, with the third harmonic maintaining its position as the most significant harmonic in terms of magnitude, while the seventh harmonic retained its status as the least influential. Moreover, it is worth noting that the minimum values of the fifth harmonic displayed a noticeable increase of approximately 30% compared to the other harmonics. This observation suggests a distinct behavior and potential sources of harmonics within the system, warranting further investigation into the underlying causes and implications of this phenomenon.

These findings shed light on the harmonic characteristics of the system under investigation, highlighting the prevalence of the third harmonic and the varying magnitudes across different harmonics. This analysis provides valuable insights into the harmonic composition and distribution within the network, aiding in the identification of potential sources and facilitating the development of appropriate mitigation strategies.

The behavior in Case 8 was comparable; however, the minimums of the third, fifth, and seventh harmonics (H3, H5, and H7) increased by up to 60% in comparison to previous cases. Finally, Case 9 demonstrated the most significant harmonic behavior, with the dominance continuing in the third harmonic and its peaks reaching a magnitude of 4.5%. Moreover, the increase in the minimum values was substantial, reaching up to 300% compared to other cases (refer to Figure 7a). The analysis of the maximum THD behavior in loads, as depicted in Figure 7b, revealed that Cases 6 and 7 exhibited higher harmonic levels compared to other cases. Conversely, during the connections of EVs, Case 9 displayed a lower THD value.

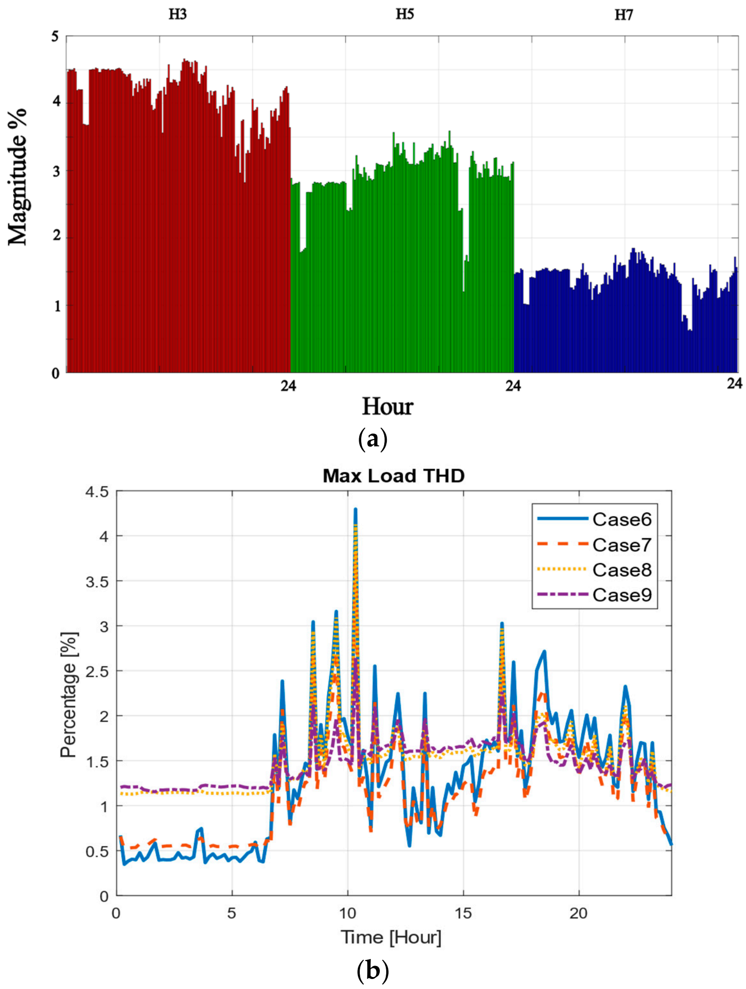


Figure 7. Harmonic behavior. (**a**) Case 9; (**b**) THD.

3.4. Hosting Capacity Limited by Harmonics

One crucial parameter in an electric distribution network with distributed generators and loads such as electric vehicles is the determination of hosting capacity. Traditionally, the analysis of this parameter relies on the limits of power supply quality and the thermal limits of network components. However, there is a limited number of studies addressing hosting capacity specifically considering harmonics.

Within the scope of this study, a hosting capacity analysis was undertaken to assess the influence of harmonic values recorded at customers' premises on the power distribution network. The analysis focused on a specific scenario, namely, Case 9, which encompasses a diverse distribution of both PV system EVs across the network's loads. By examining this particular case, this study aimed to examine the potential repercussions of harmonics on the network's overall performance and functionality. A base case was established with 55 EVs, each with a nominal power rating of 7.2 kW and an average energy consumption of 50.4 kWh, and 55 PV systems, each with a nominal power rating of 5 kW. Through MATLAB simulations, the number of EVs in the system was increased in multiples of their nominal power ratings while ensuring that the maximum THD and individual harmonic distortions remained in compliance with the IEEE 519-2022 standard (see Table 3). The results indicate that while the system can accommodate the connection of up to 104 EVs, the limitation on the third harmonic restricts the number of vehicles that can be connected to 65. The analysis also considered the probability function of connecting vehicles at different times.

Table 3. Maximum Load Total Harmonic Distortion.

EVs Connected	Max THD (%)	Max Harmonic (%)				
		3th	5th	7th	9th	11th
55	2.64	1.61	1.66	0.71	1.18	0.71
65	5.44	4.73	3.51	1.93	1.48	0.77
104	8.08	7.05	4.95	3.33	1.65	0.82

4. Conclusions and Future Work

This study aimed to investigate the impact of harmonics produced by EV charging stations on an electric distribution network with a high level of photovoltaic generation. Two distinct scenarios were examined, one with distributed photovoltaic power generation and the other with centralized generation. The results indicate that the scenario with single photovoltaic generation and EVs distributed throughout the system had the poorest performance. Overvoltages were observed at the terminals of nearby users, while undervoltages were observed at nodes further away from the system. When the harmonic analysis was added, it was found that undervoltages improved in this case. However, overvoltages were still observed at the terminals, and it was also observed that THD was higher at all nodes in the system. These findings highlight the importance of considering multiple factors when evaluating the performance of an electrical system with distributed electric vehicles and photovoltaic generation. The analysis of both voltage and harmonic distortion is crucial in identifying potential issues and developing strategies to address them. Further research is necessary to investigate the interaction between electric vehicles, photovoltaic generation, and other components of the electrical grid, such as energy storage systems, and to develop more comprehensive approaches for evaluating the performance of these systems. This research reveals that harmonics resulted in considerable variations in the voltage, current, and power of the substation transformer, with the magnitude of the third harmonic exceeding 300% compared to other cases. This study also collected information on the magnitude and angle values of harmonics for EVs and charging stations by directly measuring them at the battery terminals, enabling a comprehensive analysis of the entire energy conversion system of both the station and the EV. Upon reviewing the hosting capacity of Case 9, considering harmonics, it was observed that the high values obtained from the third harmonic decrease the total number of electric vehicles that the network can accommodate by 37.5% in comparison with a grid without PV and harmonics. Expanding the harmonic analysis with a greater number of electric vehicle brands is required, and it is also important to examine the effect of charging station efficiency. Additionally, it is necessary to conduct an analysis involving a wider variety of load types to verify their interaction with EVs, such as heat pumps, motors, and thermal generators, among others.

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Data Availability Statement: The data and simulation files used in this study are available at https://github.com/davilamds/harmonicsEVPV_2 (accessed on 15 May 2023).

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