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Prospective Analysis of Massive Integration of Electric Vehicle Chargers and Their Impact on Power Quality in Distribution Networks

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Abstract: The increasing presence of electric vehicles (EVs) requires a thorough understanding of their impact on distribution assets. EV chargers are characterized as nonlinear and multi-state loads due to their unique electrical consumption patterns. This paper presents a comprehensive study focused on modelling diverse EV charging units deployed in the industrial, commercial, and residential sectors. To conduct this analysis, a simulation environment utilizing the ETAP tool is employed, taking into account time variations. This approach facilitates the comprehension and anticipation of the effects that EV charging may impose on distribution networks, thereby supporting well-informed decision-making for the adaptation and enhancement of the electrical system. Detailed data on current and voltage from operational EV charging stations were collected to create consumption, current, voltage, and harmonic profiles for these charging units. Subsequently, general models or libraries applicable to Level 1, Level 2 and Level 3 EV chargers available in Colombia were developed. These models underwent rigorous validation and were subjected to a comprehensive analysis using the IEEE 13-bus test system. The research yielded valuable insights and conclusions regarding the integration of EV chargers into the current Colombian distribution systems, as well as the potential impact of adopting these devices on power quality issues within the distribution grid. This study contributes to the improved management of distribution assets, thereby facilitating the integration of sustainable electric mobility in the national electrical system.

Keywords: electric vehicles; non-linear loads; distribution system; charging modes; charging levels; sustainable mobility; energy quality

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1. Introduction

The growing adoption of electric vehicles (EVs) has marked a significant shift in the mobility paradigm, bringing promises of sustainability and emission reduction [1–4]. These battery-powered vehicles represent a crucial alternative to internal combustion engine vehicles, aligning with global efforts to address climate change. However, this shift towards electric mobility not only involves the transition in the type of vehicle but also poses considerable challenges to charging infrastructure, particularly in electrical distribution networks [5–8].

The increase in demand for electrical energy derived from the widespread charging of EVs raises crucial questions about the capacity and efficiency of existing distribution networks. The simultaneous charging of numerous vehicles may create significant stress on the existing electrical infrastructure, affecting the stability and reliability of the supply [9,10].

In this context, understanding and anticipating these impacts becomes imperative to ensure a smooth transition to electric mobility without compromising service quality or increasing the risks of network failures [11].

However, nonlinear loads such as EV chargers can cause power quality issues on distribution feeders, which in turn may reduce the lifetime of distribution assets [12,13]. Power quality refers to the voltage and current waveforms supplied by the grid operator to its customers and becomes a cause for concern when deviations in voltage magnitude, interruptions in power supply or variations in transient voltages and currents occur. In addition, power quality covers aspects such as harmonic distortion, phase unbalance and voltage fluctuations [14–16]. Among these factors, harmonic currents are particularly relevant, as they can reduce the lifetime of electrical equipment and cause problems in sensitive electrical systems, such as PLC systems, frequency converters, encoders and automation and control systems.

Distribution network operators, through their engineers in charge of evaluating the incorporation of new loads into the system, face the challenge of validating and properly interpreting the entry of new multi-state, unbalanced and distorted loads, such as EV chargers [17–19]. In this case, they aim to anticipate and understand the potential impacts that these electric chargers would have on the quality of power provided by the distribution system to their customers.

Studying the impacts of EV chargers on distribution networks not only highlights challenges but also opens the door to innovative opportunities; furthermore, it enables governments to make informed policy decisions and incentivize sustainable EV adoption. This planning ensures that the advantages of EV adoption (such as reduced air pollution and improved air quality), are accessible to all, especially communities with limited transportation options or charging infrastructure such as those in developing countries. The implementation of smart technologies, efficient load management, and the promotion of distributed generation are some strategies that could help alleviate pressures on electrical networks [20–22]. However, these studies are rarely carried out in developing countries such as Colombia, which does not have a clear policy regarding the imminent massification of EV chargers.

According to data from the Colombian National Traffic Registry, there has been a notable increase in the number of registered electric vehicles in recent years. In the second quarter of 2019, more than seven hundred zero-emission buses were incorporated in Bogota. During the first six months of 2022, a total of 1891 EVs were registered in Colombia, with a monthly average of 315 units. This increase is the result of incentive policies and a renewed environmental awareness of society in general. With the continuous launch of new electric vehicles on the market, this trend seems to be constantly growing.

The main objective of this work is to assess the impact of the massive integration of EV chargers on the power quality of distribution networks in Colombia. Evaluating the impact of EV chargers in distribution networks of developing countries is essential for their sustainable development. These studies facilitate infrastructure planning by anticipating the increased electricity demand arising from widespread EV adoption. Understanding usage patterns and charging behaviors, help governments and utilities to strategize upgrades to distribution grids, ensuring the accommodation of additional load without causing disruptions or overloads. In this way, eventual blackouts can be avoided resulting from sudden surges in power demand during peak charging times. Moreover, analyzing EV impact helps to align the charging infrastructure with renewable energy sources, enabling better integration and optimization of clean energy for transportation [23–25]. The main features and contributions of this paper are as follows:

- A characterization of different EV chargers available in the Colombian market is carried out through field measurements.
- An assessment of the impacts of EV chargers on power quality is carried out in a benchmark test system that emulates a typical Colombian distribution network.

- The methodology and study described in this paper are aimed at assisting planning experts in designing distribution systems capable of adapting to a massive adoption of EVs.

The rest of the document is structured as follows: Section 2 describes the implemented methodology and the characterization of the test network. Section 3 presents the tests and results on the test system considering three time horizons or scenarios. Finally, Section 4 presents the conclusions of the study.

2. Methodology

To anticipate the impacts on power quality resulting from the massive use of EV chargers in Colombian distribution networks, several field measurements were taken using power quality analyzers. This information allowed to characterize several EV chargers. Subsequently, a library of models was created for Level 1, Level 2 and Level 3 EV chargers available in the Colombian market. The prospective analyses were developed using ETAP simulation software, in the IEEE 13-bus test system, adapted to reflect a typical distribution system in Colombia. The modifications were carried out taking into account the typical demand curves present in the current load scenario for residential, commercial and industrial users in the country. Three scenarios are considered: the current state of the network (scenario 1) and demand projections for 2030 and 2040 (scenarios 2 and 3, respectively).

2.1. Collected Information

To characterize the main electrical parameters of the most common EV chargers available in Colombia, several measurements were carried out using network analyzer equipment. These measurements were performed upstream of the chargers mentioned below.

Table 1 presents the EV chargers that were monitored in the study, as well as their classification in terms of charging mode and level. In this case, all EV chargers used in the tests are off-board. Note that some of them feature Charging Mode 1 which is still currently used in Colombia; nonetheless, it is expected that this charging mode won't be used in the future. These categories are defined according to the relevant regulations, specifically NTC-IEC 61851-1 and Resolution 40223 of 2021 of the Colombian Ministry of Mines and Energy (MME), which address aspects related to the safety and charging power of these devices. The following charging levels are considered:

- Charging Level 1: it uses a standard Alternating Current (AC) outlet. Its power rating is less than 3.7 kilowatts [kW].
- Charging Level 2: it requires the installation of a charging station with an alternating current (AC) connection. Its rated power is between 3.7 kilowatts [kW] to 22 kilowatts [kW].
- Charging Level 3: it consists of a fast load with connection to Alternating Current (AC) or Direct Current (DC). Its rated power is greater than 22 kilowatts [kW] in AC and greater than 50 kilowatts [kW] in DC.

Table 1. Summary of measured EV chargers.

Charger (Manufacturer/Reference)	Charging Mode	Charging Level	Estimated Charging Time (h)
BYD/EVA080KS/01	3	3	2.5
Enpower/CH4100-9620	1	1	18.5
Kingpan KP900F-60Q	1	1	15.2
eHome/T2C32	2	1	8.3
BYD/EVA080KS/01	3	2	4
ZDWL/Z WDP-032415	1	2	6
Chevrolet/EVSE-CSSS56600012-1003	2	1	33

Table 2 presents a summary of the electrical parameters measured for the EV chargers described in Table 1. These parameters include voltage, current, active and reactive power,

power factor and individual percentage of harmonics present in the current waveform of each charger. It is worth mentioning that the EVA080KS fast EV charger operates at low load and is single-phase connected, therefore the presence of third harmonics. The main objective of this activity was to create a real library for each electrical charger to be used at a later stage of the study in the ETAP simulation software.

Table 2. Parameters obtained from power quality measurements for different EV chargers.

	Charger						
Parameter	**EVA080KS 01/k7**	**CH4100-9620**	**KP900F-60Q**	**T2C32**	**EVA080KS 01/e5**	**ZWDP**	**CSSS566 00012**
Voltage (V)	497.4	120.29	114.16	221.8	284.9	216.9	108.35
Current (A)	80	13.1	20.7	16.7	31	26.5	7.95
Fundamental current (A)	79.97	13.0	17.4	16.6	30.6	26	7.9
Active Power (kW)	73.81	1.56	1.89	3.45	8.64	5.622	0.874
Reactive Power (kVAr)	1.563	−0.03	−1.38	−0.12	−0.72	−0.04	−0.084
Power Factor	0.98	0.99	0.81	0.99	0.98	1.00	0.99
H3 (%)	11.97	2.27	62.15	8.50	11.97	2.40	3.98
H5 (%)	5.43	3.00	16.28	4.09	5.43	2.69	5.74
H7 (%)	1.27	0.37	11.07	2.63	1.27	2.82	2.36
H9 (%)	0.96	1.02	9.57	0.60	0.96	2.06	1.03
H11 (%)	1.01	0.49	3.60	1.50	1.01	1.53	0.69
H13 (%)	0.54	0.10	3.92	1.40	0.54	1.06	0.42
H15 (%)	0.34	0.72	2.59	1.20	0.34	0.84	0.86
H17 (%)	0.22	0.65	2.66	0.49	0.22	0.31	0.42
H19 (%)	0.13	0.44	1.15	0.33	0.13	0.35	0.62
H21 (%)	0.16	0.62	1.72	0.59	0.16	0.48	0.32

2.2. Test Network

Benchmark test systems play a key role in electrical studies because they provide a standardized and consistent basis for comparison, enabling researchers, engineers, and manufacturers to assess the capabilities and limitations of new technologies, components, or methodologies. In this study, the IEEE 13-bus test system illustrated in Figure 1 was used. In this case, node 650 is the common connection point or link with the substation where all the loads of the system are aggregated.

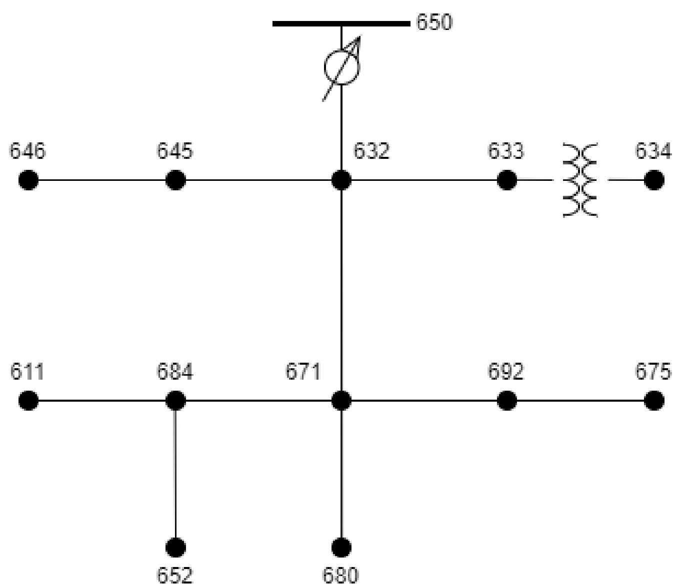

Figure 1. Single-line diagram of the IEEE 13-bus test system.

The IEEE 13-bus test system is a benchmark power system widely used in power systems research and analysis. This simplified representation of an actual power network comprises 13 buses (nodes) interconnected by transmission lines and transformers, designed to simulate various operational conditions. The system includes a mix of different types of buses and serves as a fundamental model for evaluating power flow, fault analysis, and stability studies, allowing researchers to test and compare different algorithms, control strategies, and optimization techniques.

Several modifications to the load of the IEEE 13-bus test system are carried out to simulate a typical Colombian distribution system. The electricity generated in Colombia is distributed in sectors such as residential, industrial, commercial, services, mining, construction and others. Based on the sectorized electricity consumption matrix of Colombia, each of the nodes of the IEEE 13-bus test system is classified according to the percentage of load demanded at each bus as indicated in Table 3.

Table 3. Classification of the consumption profile of the test network.

Bus	P (kW)	% of Load	Classification
611	170	4.9%	Other
632	100	2.9%	Residential
634	400	11.5%	Residential
645	174	5.0%	Residential
646	237	6.8%	Residential
652	126	3.6%	Residential
671	1255	36.1%	Industrial
675	843	24.3%	Commercial
692	170	4.9%	Commercial
Total Power	3474	100%	

2.3. Scenarios Definition and Pilot Nodes

For generating the simulation scenarios, a projection of the growth of the EV fleet in the country up to the year 2040 is used. This projection is based on the national electric mobility strategy developed by the country's Mining and Energy Planning Unit (UPME) which is illustrated in Figure 2 [26].

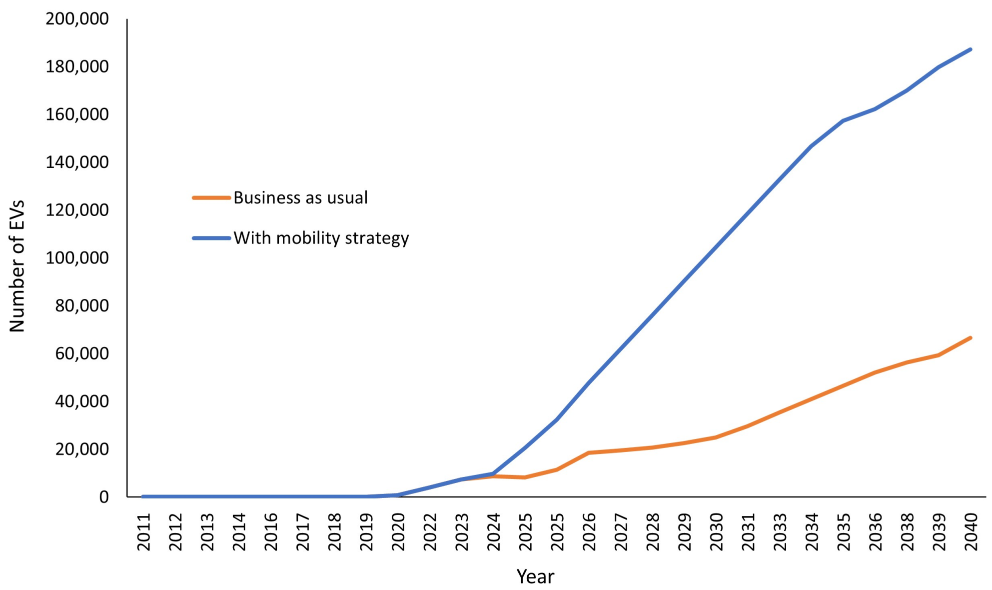

Figure 2. Projection of EV sales in Colombia.

Although the load growth is expected in all nodes of the test system, three pilot nodes are selected for detailed analysis: 652, 671 and 692 which present residential, industrial and commercial loads, respectively. In the case of the commercial and residential nodes, demand growth was assumed not only in the number of EV chargers but also in the consumption associated with the homes and commercial buildings of the network. Based on the EV sales projection presented in Figure 2, and in the absence of a government mobility strategy (business as usual), three scenarios were put forward to estimate the load growth of the aforementioned pilot nodes as shown in Table 4.

Table 4. Loadability of each scenario for different nodes of the IEEE 13-bus test system in kVA.

Scenario—Year	Bus 652	Bus 671	Bus 692	Total (Bus 650)
1—2023	121	1330	228	3822
2—2030	365	4007	685	7291
3—2040	949	10,417	1782	16,538

These scenarios are used to anticipate how the growth in the adoption of EVs will impact different segments of the electric grid, which in turn will allow for more effective planning to ensure the availability and quality of power supply in these sectors.

Note that the pilot nodes are far from the main source or substation (bus 650). This choice was made to show how power quality problems propagate through the distribution system and ultimately affect the substation, allowing for a more complete assessment of the effects of EV chargers in various areas of electric distribution systems.

To estimate the percentage share of final energy consumption by EVs in Colombia for the years 2030 and 2040 (scenarios 2 and 3, respectively), the data projected by the National Electric Mobility Strategy was used [26]. The EV participation by 2030 and 2040 considering projections of EV energy demand and the energy demand of the National Interconnected system (NIS) is computed as indicated in Equation (1).

$$Percentage\ of\ EV\ participation = \frac{EV\ energy\ demand}{Total\ energy\ demand\ (NIS)} \times 100\% \tag{1}$$

The results of these calculations provide approximate estimates of the percentage share of EVs in final energy consumption in Colombia for the years 2030 and 2040 as shown Table 5. These projections are subject to uncertainty and may vary according to factors such as government policies, EV adoption and the growth of charging infrastructure.

Table 5. Percentage of electricity demand in Colombian transportation sector.

Scenario—Year	Projected Daily Energy Demand (NIS) MWh/Day	% Electricity Demand in the Transportation Sector
1—2023	207,000	3.50%
2—2030	250,686	8.72%
3—2040	305,294	18.61%

According to Table 5, the electricity consumption of the Colombian transportation sector is estimated to account for 8.7% of the total electricity consumption of the country by 2030 (scenario 2) and to increase up to 18.6% by 2040 (scenario 3). The scenarios described in Table 5 are simulated on the IEEE 13-bus test system, adapted to reflect a typical Colombian distribution system by implementing load curves for residential, commercial and industrial sectors as indicated in Figure 3.

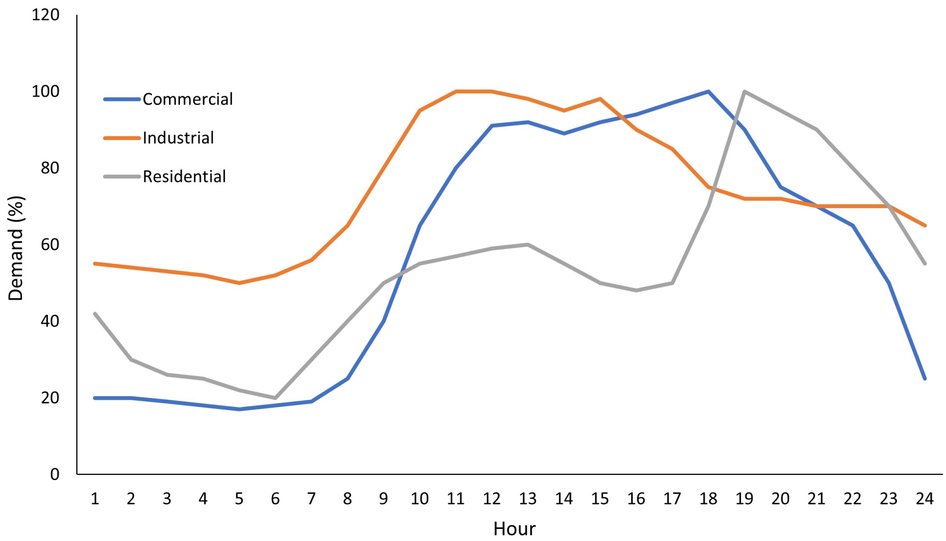

Figure 3. Demand profile of residential, commercial and industrial sectors in Colombia.

Typical users of Colombian distribution systems encompass a mix of residential, commercial, and industrial consumers. In densely populated urban areas, residential and commercial users are prevalent, while in rural regions, distribution may focus more on dispersed residential or agricultural users. Typical distribution voltages range between 110 V and 440 V for residential and commercial users, while for industrial applications and some commercial users, voltages can vary up to 13.2 kV in medium-voltage networks.

The topology of distribution networks in Colombia varies based on the region. Urban areas commonly feature overhead distribution networks, whereas rural and mountainous zones may involve overhead lines and underground systems due to geographical conditions. In terms of technologies, there is an ongoing transition towards digitalization and the implementation of smart meters to enhance network management, efficiency, and data collection for analysis and control of distribution systems [27].

In Colombia, a typical demand curve of a residential user experiences its highest energy consumption between 18:00 h and 21:00 h with a minimum demand between 22:00 h and 5:00 h. The commercial demand curve shows higher consumption between 9:00 h and 22:00 h, coinciding with the usual opening and closing hours of commercial establishments. The industrial demand curve reflects the period of maximum energy consumption from 7:00 h to 17:00 h, by the usual working hours of Colombian companies. It is important to highlight that in this sector, even during off-peak hours, consumption exceeds 50% of the peak demand. This is due to companies that operate continuously, keeping extended working hours.

2.4. Adaptation of Demands in Pilot Nodes

The network equivalent connected at node 650 was modified adding typical voltage harmonics, as shown in Figure 4. In this case, the voltage waveform presents a Total Harmonic Distortion (THD) of 2.15%. A typical sub-network of a residential complex was included in the simulation, considering that the parking lots have charging stations for EVs. It was assumed that, on average, there is one charger for every two vehicles.

Node 671 was configured with an industrial-type load profile for the base scenario. However, in scenarios 2 and 3 projected for the years 2030 and 2040, respectively, a significant increase in demand for industrial-type chargers was considered. The load profile at node 671 follows the public transport schedules of major cities in Colombia, which run from 5 a.m. to 10 p.m. During this period, EV chargers remain in standby mode. In the remaining time, they are in full charge condition to ensure the recharging of the transport fleet.

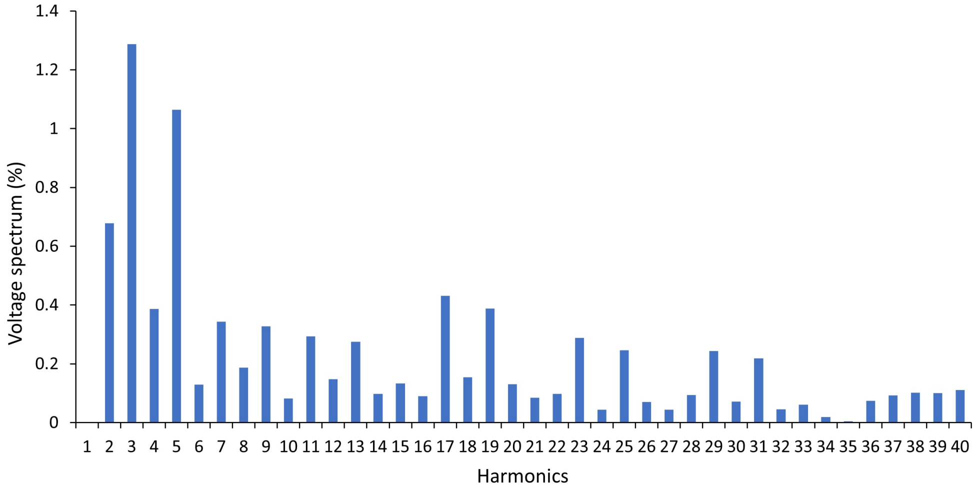

Figure 4. Harmonic voltage spectrum at node 650.

A commercial charging profile is initially established for the base scenario in node 692. However, scenarios 2 and 3 incorporate typical loads from chargers with a semi-fast charging type. These chargers are located in the parking lots of shopping malls and play a key role in the Colombian electricity system. In this context, Level 2 chargers are included, taking as a reference the measurements made in the field. The incorporation of semi-fast chargers in scenarios 2 and 3 represents an important variation in the charging demand in node 692.

Node 652 is modeled as a typical sub-network of a residential complex, considering that the parking lots have charging stations for EVs. It has been assumed that, on average, there is one charger for every two vehicles.

According to the changes made in the pilot nodes under study, the proposed scenarios are modeled in the ETAP software and simulated for collecting the electrical parameters of interest: demand profile, voltage unbalance, harmonic content, voltage drop or voltage regulation.

3. Tests and Results

The results presented in this section were obtained through simulations of the test system in two modes: static (steady-state load flow and harmonic flow at nominal loads) and dynamic (time domain load flow). Several electrical parameters were analyzed, including harmonic distortion, voltage regulation, voltage unbalance and demand curves.

3.1. Harmonic Distortion

Harmonic distortion refers to the alteration of a periodic waveform from its original sinusoidal shape. It occurs when additional frequencies, known as harmonics, are introduced to the fundamental frequency of an electrical signal. These harmonics are multiples of the fundamental frequency and usually arise due to nonlinearities in electronic devices, such as EV chargers. High levels of harmonic distortion can lead to disruptions in electrical systems, causing issues such as equipment malfunction, overheating, and power quality deterioration [28]. The assessment of harmonic distortions in voltage and current is a fundamental indicator of the quality of the electrical wave [29]. The THD represents the combined effect of all harmonics present in relation to the fundamental frequency of an electrical waveform. THD is expressed as a percentage and provides an indication of how much the signal deviates from a pure sinusoidal waveform. Lower THD values indicate a cleaner and more efficient electrical system, while higher THD levels suggest greater distortion and potential issues in power quality, affecting equipment performance and reliability.

Figure 5 presents an analysis of the THDv in the nodes of the IEEE 13-bus test system in the three specific scenarios previously defined. In the base scenario, which does not consider the proliferation of EV chargers, it is observed that THDv values remain below 2.5%. However, as EV chargers are progressively introduced, a significant increase in voltage harmonics levels is evidenced.

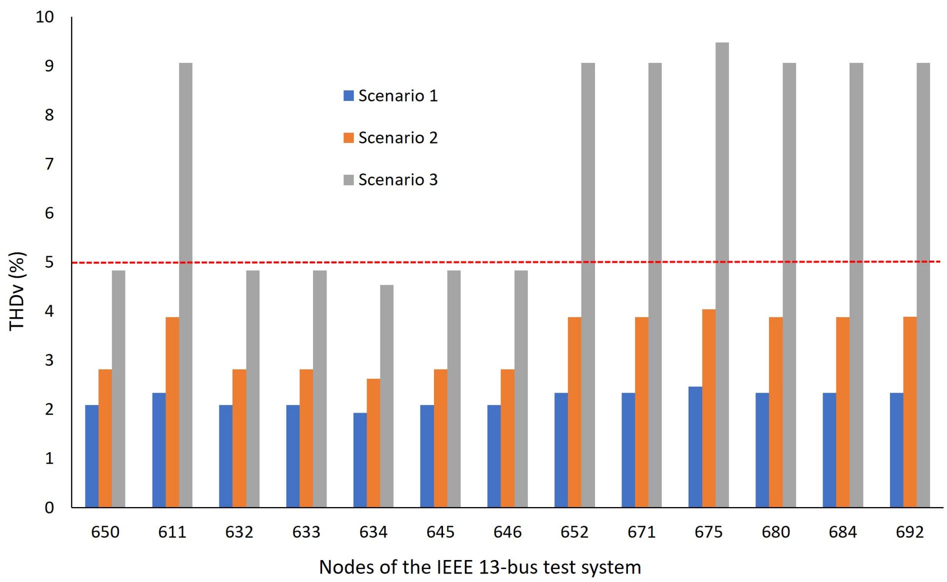

Figure 5. Total harmonic distortion of the voltage wave (THDv).

Nodes directly linked to node 671 and neighboring nodes are the most affected by the increase of the THDv. This situation is explained by the fact that node 671 is the main connection point for the installation of Level 3 EV chargers, also known as fast charging. Due to their elevated power usage, these devices create more significant disruptions that propagate to adjacent nodes, impacting the overall electrical waveform quality. By 2023 (scenario 2), THDv at the directly affected nodes has nearly reached 4.0%, while node 650 (the main node of the system) experiences a THDv of 2.8%. These values are within the limits recommended by the IEEE 519 standard, which establishes a threshold of 5% for total harmonic distortion in electrical systems (indicated as a dashed red line in Figure 5).

Regarding the forecast for the year 2040 (scenario 3), it is evident that harmonic distortion levels are above the regulatory standards. This significantly affects the nodes with EV chargers, as well as nearby nodes, where THDv values reach 9%. These results indicate a remarkable propagation of harmonics throughout the system.

Consequently, for the increase in EV chargers expected by 2040, the electric system will not comply with the harmonic distortion limits established in IEEE 519. This situation poses significant challenges in terms of power quality and suggests the urgent need to implement harmonic mitigation and control strategies to preserve the integrity and optimal operation of the power grid if a significant growth in the adoption of EVs is expected.

Figure 6 shows the total harmonic current distortion rate (THDi) for each of the nodes of the test system. It is important to highlight that nodes 611, 645, 646, 652, 680 and 684 do not show a THDi value because they do not have associated loads. Additionally, it is observed that there is no defined limit as in the THDv. This is because such limit varies depending on the load current of each node and the short-circuit level of the associated connection point. On the other hand, the network operator and/or energy supplier will monitor and control the THDv and not the THDi, because the latter is directly attributed to the user's loads, and as long as these values do not affect the quality of the operator's voltage waveform, it is not relevant for the operator.

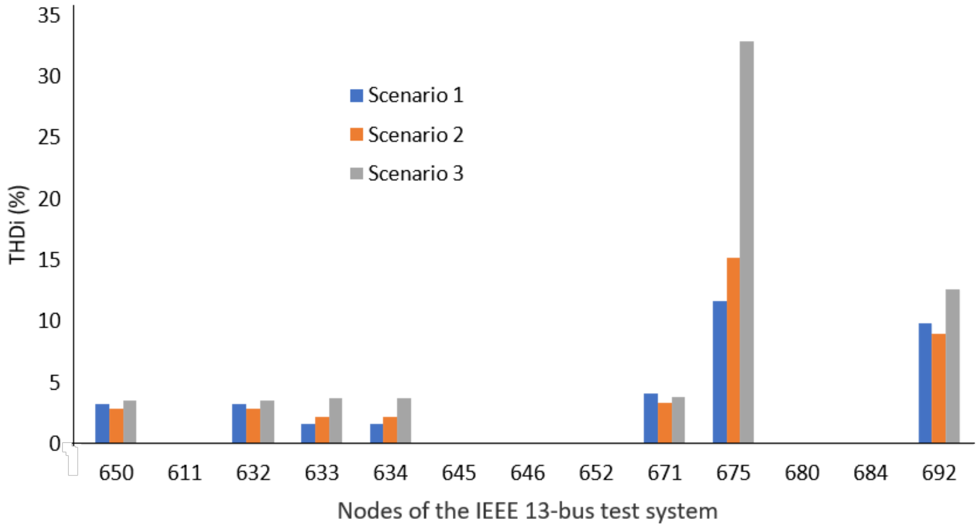

Figure 6. Total harmonic distortion of the current wave (THDi).

3.2. Voltage Regulation

Voltage regulation in distribution networks refers to the ability to maintain a stable voltage level within an acceptable range despite fluctuations in load demand or variations in power supply. When voltage levels deviate excessively, it can lead to inefficiencies, equipment damage, or operational issues [30].

According to current regulations, the voltage at nodes classified in Level 2 must be within the range of 90% to 110% of the nominal voltage value. This means that any significant deviation beyond these limits signifies an adverse effect on the quality of electricity supplied to users. Hence, it is essential to evaluate if corrective measures are necessary to guarantee compliance with electrical power quality standards in the examined scenarios. Figure 7 shows the voltage profile at each node of the IEEE 13-bus test system for the different scenarios analyzed. In scenario 1, where the influence of EVs is not considered, the steady state voltages remain above 90% of the nominal voltage at all nodes, thus complying with regulatory standards.

As the load increases in the projection for the year 2030, high voltage drops are observed in the main affected nodes, with voltages reaching values of 95% in node 652. Even with these voltage drops, in scenario 2, the system still complies with the Colombian normative regarding voltage limits. In this case, for voltage Level 2 (1 kV < Vn < 30 kV), voltage variations below 90% are not allowed for periods longer than 1 min.

In the scenario projected for the year 2040, a significant increase in load is observed, resulting in voltages below 90% of the nominal value, which violates the established standards, especially at node 652. This situation is critical, as it represents a drastic decrease in voltage quality in various nodes.

Due to the particular configuration of the system, residential users are the most affected by these voltage drops. This scenario underlines the need to take load management measures to avoid the occurrence of voltages below acceptable limits with the projected increase of EV chargers. Also, a thorough review of the electrical infrastructure and careful planning may be required to ensure that the system can meet the increased energy demand from EV adoption.

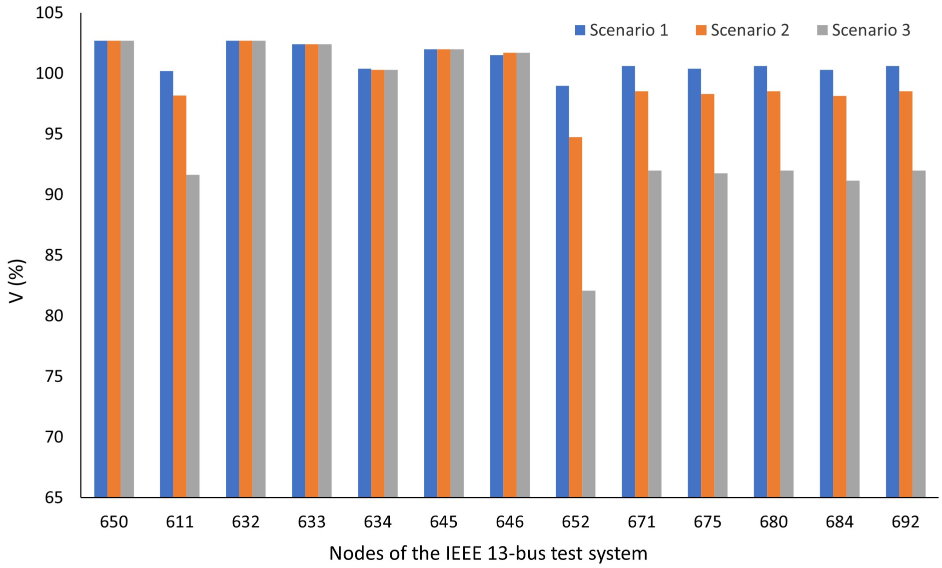

Figure 7. Voltage regulation in the IEEE 13-bus test system.

3.3. Voltage Unbalance

Voltage unbalance is a relevant parameter in electrical distribution systems. It is defined as the ratio between the negative and positive sequence voltages. Voltage unbalances in the power supply impact both the utility company and the final consumer. Excessive voltage unbalance in normal operation represents a concern in terms of power quality [31,32]. Voltage unbalance also causes overheating of three-phase induction motors in industrial systems, as well as non-typical harmonics by three-phase converters and unwanted power losses in electrical distribution networks [33,34]. Due to the particularities of Level 1 EV chargers, which are connected to single-phase systems, this may represent a new source of voltage unbalance in distribution systems.

Figure 8 illustrates the voltage unbalances at node 650, which constitutes the connection point with the external grid. The voltage unbalance in scenario 1 ranges between 0.28% and 0.66% depending on the hour of the day. These values are within the acceptability requirements of the Colombian electrical system.

In scenario 2, there is an observed rise in voltage imbalance of approximately 1.7% at node 650. However, This value is still within the standards allowed by Colombian regulations, which establish that, for systems with a voltage equal to or lower than 69 kV, voltage unbalance must be kept below 2.0%. However, the most distant nodes from the source reach unbalanced values of up to 3.15%, which may lead to power quality issues for these users.

A critical increase in voltage unbalance is observed in scenario 3, reaching a peak value of 2.89% and being above 2.0% from 10:00 h to 22:00 h. These percentages of voltage unbalance exceed the current regulation limits and become a critical issue for the distribution system operator. Furthermore, according to the performed simulation, the nodes far away from the main grid such as node 675 experience a higher voltage unbalance of up to 6.4%.

Power quality fluctuations notably affect users located near EV connection points in both residential and commercial areas. It is worth mentioning that the integration of EV chargers into residential and commercial nodes was carried out randomly to simulate existing practices in Colombia's sector, as there are no specific guidelines in this regard. This underlines the need for more rigorous planning in the future, to manage an increase of load related to Level 1 and Level 2 EV chargers.

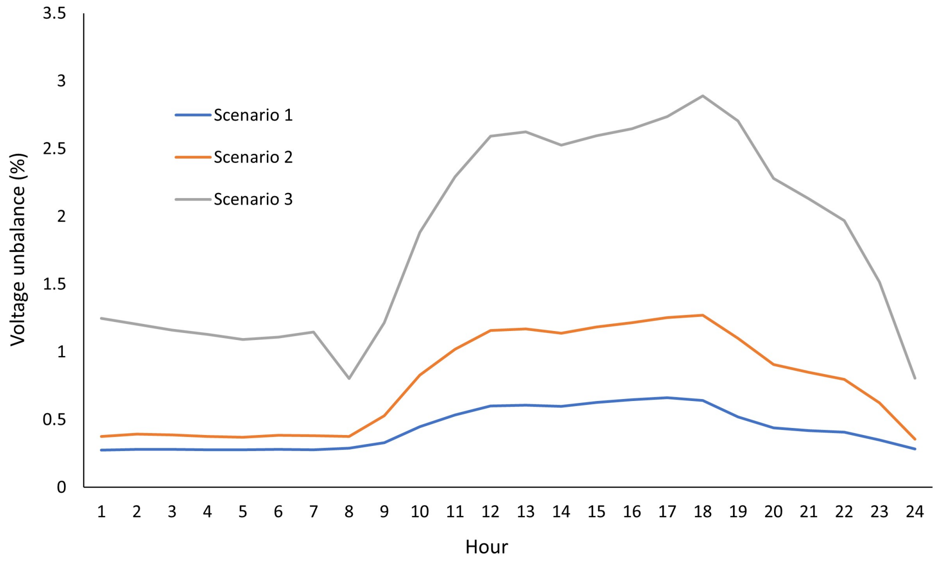

Figure 8. Voltage unbalance in node 650 for different scenarios.

Figure 9 illustrates the unbalances associated with each node in the three scenarios under study. This analysis was performed using a steady-state load flow approach, which means that the system is evaluated when it is operating at its rated capacity and with the EV load running simultaneously. In scenario 2 nodes 611, 652, 671, 675, 680, 684, and 692 exceed the limit of voltage unbalance established by the regulation. The unbalanced values deteriorate further for scenario 3. In this case, even the main node is non-compliant.

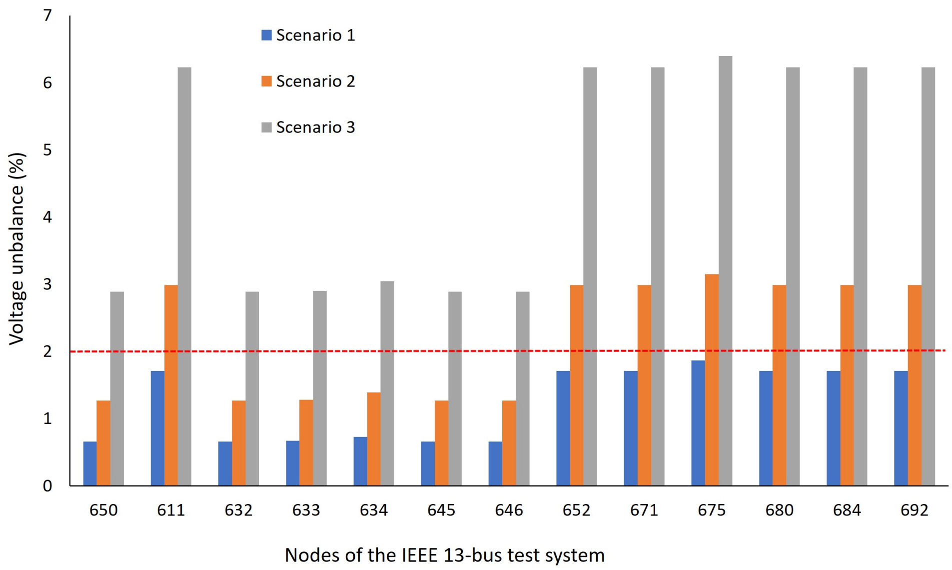

Figure 9. Voltage unbalance at the test system nodes.

3.4. Demand Curve

The daily demand curve plays a critical role in assessing EV integration, directly influencing how centralized energy is managed and distributed by the power system operator. Integrating EV charging adds to the overall demand for electric power within the system. Furthermore, this extra demand can fluctuate notably based on the charging behaviors of EV owners. Typically, charging activity peaks during nighttime hours when vehicles are parked at homes, residential areas, or charging stations.

Figure 10 presents the demand curve of the test system under different scenarios. The blue line (scenario 1) is a mix of demand curves corresponding to the residential, commercial and industrial sectors as indicated in Figure 3 for the year 2023. In this scenario, the effect of EV chargers on the demand curve is negligible. Nonetheless, in scenarios 2 and 3 there are important changes on the demand cure. This is mainly due to the increase in load during the night periods, with a higher energy consumption between 22:00 h to 6:00 h. This change in the demand profile is a direct consequence of the incorporation of EVs in the system. In general, EV owners tend to charge their vehicles at night, taking advantage of time availability. This behavior may reverse traditional demand trends, where peak consumption tends to occur during daytime hours due to industrial and commercial activity.

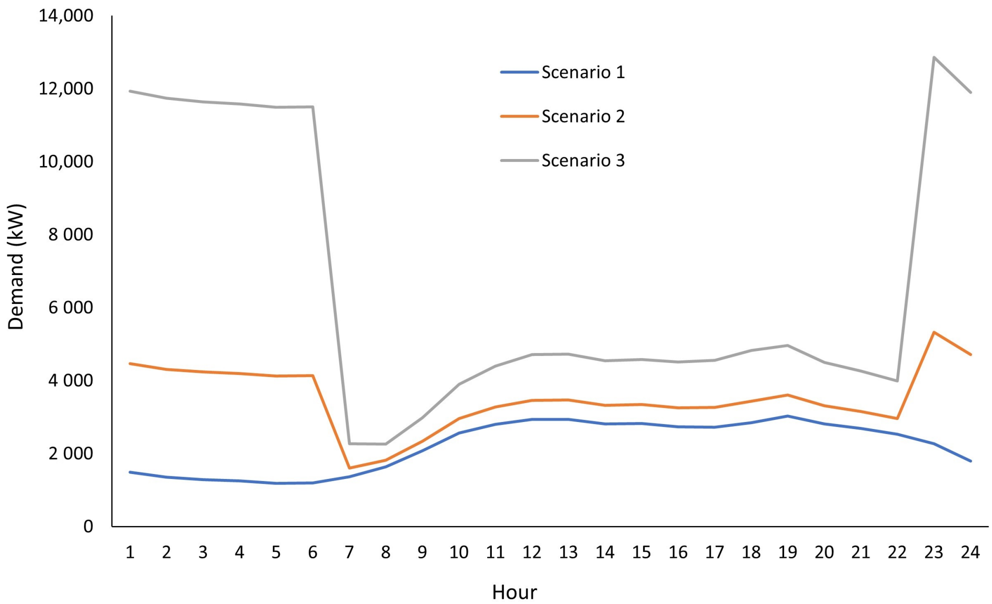

Figure 10. Demand curve for different scenarios.

The shift in demand profile has significant implications for how the electricity system is managed and operated, as it requires adapting power supply and distribution strategies to accommodate the heightened demand for nighttime charging. Moreover, it's crucial to strategically plan and optimize EV charging infrastructure to efficiently handle the increased demand during these specific periods. This planning helps prevent overloading of the power grid during peak charging hours.

3.5. Summary of Results

Tables 6–8 provide a detailed summary of the results obtained in the simulations for each of the studied scenarios, where VU in the last column stands for voltage unbalance. The values that are outside the limits established by the current regulation are highlighted in bold letters.

Table 6. Summary of results for scenario 1.

Node	P (kW)	PF (p.u)	%V	THD i (%)	THD v (%)	VU (%)
650	3518.0	0.92	102.7	3.20	2.09	0.66
611	170.3	0.905	100.2	—	2.34	1.71
632	100.0	0.865	102.7	3.2	2.09	0.66
633	—	—	102.4	1.61	2.09	0.67
634	399.9	0.810	100.4	1.61	1.93	0.73
645	174.1	0.850	102	—	2.09	0.66
646	236.6	0.837	101.5	—	2.09	0.66
652	125.5	0.830	98.98	—	2.34	1.71
671	1255.0	0.865	100.6	4.05	2.34	1.71
675	842.9	0.877	100.4	11.6	2.47	1.87
680	—	—	100.6	—	2.34	1.71
684	—	—	100.3	—	2.34	1.71
692	170.1	0.747	100.6	9.84	2.34	1.71

Table 7. Summary of results for scenario 2.

Node	P (kW)	PF (p.u)	%V	THD i (%)	THD v (%)	VU (%)
650	6968.0	0.9547	102.7	2.88	2.82	1.27
611	167.2	0.905	98.17	—	3.88	**2.99**
632	100.0	0.955	102.7	2.88	2.82	1.27
633	—	—	102.4	2.18	2.82	1.28
634	399.9	0.810	100.3	2.18	2.63	1.39
645	174.0	0.850	102	—	2.82	1.27
646	236.6	0.867	101.7	—	2.82	1.27
652	345.6	0.964	94.76	—	3.88	**2.99**
671	3897.0	0.968	98.53	3.34	3.88	**2.99**
675	845.0	0.877	98.32	15.14	4.04	**3.15**
680	—	—	98.53	—	3.88	**2.99**
684	—	—	98.13	—	3.88	**2.99**
692	635.3	0.991	98.53	8.98	3.89	**2.99**

Table 8. Summary of results for scenario 3.

Node	P (kW)	PF (p.u)	%V	THD i (%)	THD v (%)	VU (%)
650	15,564.0	0.9408	102.7	3.55	4.83	**2.89**
611	156.1	0.905	91.62	—	**9.06**	**6.23**
632	100.0	0.941	102.7	3.55	4.83	**2.89**
633	—	—	102.4	3.74	4.83	**2.9**
634	399.9	0.810	100.3	3.74	4.54	**3.05**
645	174.0	0.850	102	—	4.83	**2.89**
646	236.6	0.867	101.7	—	4.83	**2.89**
652	883.0	0.988	**82.09**	—	**9.06**	**6.23**
671	10160.9	0.946	92	3.8	**9.06**	**6.23**
675	845.2	−0.998	91.76	**32.86**	**9.48**	**6.4**
680	—	—	92	—	**9.06**	**6.23**
684	—	—	91.15	—	**9.06**	**6.23**
692	1666.5	0.991	92	**12.58**	**9.06**	**6.23**

4. Conclusions

The proliferation of EVs in distribution networks constitutes additional sources of imbalances. Therefore, it becomes crucial to conduct thorough planning to accommodate the widespread adoption of these loads. Without a proper planning approach, the system's organic growth may lead to voltage imbalances surpassing regulatory limits.

This study conducted a prospective analysis of the extensive integration of EVs in Colombia, projecting ahead to 2030 and 2040. Based on the simulations, it can be inferred that the current test system possesses adequate capacity and infrastructure to accommodate the expected increment in demand resulting from the introduction of EV chargers until 2030 without encountering major technical issues. This preliminary evaluation highlights the adaptability of the existing power grid to address the initial requirements of electric mobility. However, by 2040, a different scenario is anticipated. The results suggest that, by that period, the system could face significant challenges in terms of power quality, voltage regulation and demand management. More specifically, it is anticipated that the system will no longer meet regulatory power quality standards.

In summary, while the present electricity system seems equipped to manage the expected rise in EV usage in the foreseeable future, it is crucial for regulatory bodies and planning agencies to work in tandem for extensive, forward-looking planning. This involves the formulation of appropriate regulations that support efficient and safe electric mobility, as well as a continued focus on improving the quality of electric power, which will ultimately benefit society at large and contribute to the long-term economic development of the country.

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