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# Optimizing EV charging stations: a simulation-based approach to performance and grid integration

**William Fabián Sánchez Díaz, Jonatan Tolosa Vargas, Fredy Martínez**
Facultad Tecnológica, Universidad Distrital Francisco José de Caldas, Bogotá D.C, Colombia

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**ABSTRACT**

This study addresses the optimization of electric vehicle (EV) charging stations, focusing on enhancing performance and grid integration through a comprehensive simulation approach. By employing advanced simulation tools in Simulink® and MATLAB®, alongside electrical installation planning with SIMARIS®, we meticulously analyze the charging process, infrastructure requirements, and their implications on the power grid. Our results demonstrate significant improvements in charging station efficiency and reliability, highlighting the effectiveness of our proposed control strategies and harmonic mitigation techniques. Notably, the integration of renewable energy sources emerges as a pivotal factor in reducing operational costs and carbon emissions, furthering the sustainability of EV charging solutions. The research delineates the environmental benefits, emphasizing the reduction of greenhouse gas emissions and enhancement of urban air quality, pivotal in the global shift towards cleaner transportation modes. This work contributes valuable insights into the design and grid integration of EV charging stations, offering a scalable model for future infrastructure development. It serves as a critical resource for engineers, policymakers, and stakeholders in the realm of electric mobility, advocating for a strategic transition to EVs supported by robust and efficient charging infrastructure.



***Corresponding Author:***

Fredy Martínez
Facultad Tecnológica, Universidad Distrital Francisco José de Caldas
Carrera 7 No 40B-53, Bogotá D.C., Colombia
Email: fhmartinezs@udistrital.edu.co

## 1. INTRODUCTION

The pervasive use of diesel engines in transportation significantly exacerbates global environmental pollution, contributing extensively to black carbon emissions. This form of pollution is particularly concerning due to its direct association with climate change and its ability to diminish air quality, impacting ecosystems and human health worldwide [1], [2]. Studies have shown that diesel exhaust, rich in PM2.5 particles, directly correlates with increased instances of respiratory and cardiovascular diseases, underlining the pressing need for alternative, cleaner transportation methods [3], [4]. The urgency of this issue is magnified in densely populated urban areas, where the concentration of diesel vehicles amplifies their detrimental health effects. Consequently, the transition to electric vehicles (EVs) emerges as a vital solution to mitigate these environmental and health risks, signaling a pivotal shift towards sustainable urban mobility.

In the face of these environmental challenges, Colombia has emerged as a leader in Latin America by aggressively pursuing policies aimed at reducing greenhouse gas emissions from public transportation. By integrating electric buses into the fleets of major cities such as Bogotá, Medellín, and Cali, the country is setting a benchmark for environmental responsibility and innovation in urban transit [5]–[7]. These initiatives reflect a broader global movement towards sustainability, highlighting the importance of EVs in achieving reduced emissions and cleaner air. Moreover, these efforts align with international environmental goals and demonstrate the feasibility of transitioning to electric mobility on a large scale, even in emerging economies. This strategic pivot not only addresses immediate environmental concerns but also fosters long-term public health benefits by significantly lowering pollution levels [2], [8].

The shift towards EVs is intricately linked to the development and adoption of advanced energy storage technologies, with lithium-ion batteries at the forefront of this transformation [9]. These batteries' efficiency in energy conversion and storage capabilities has been pivotal in making EVs a viable alternative to their diesel counterparts. However, challenges remain in enhancing battery life, reducing charging times, and improving overall energy density to meet the demands of daily transportation needs [10]. Research and innovation in battery technology continue to break new ground, offering hope for overcoming these hurdles and unlocking the full potential of electric mobility [11], [12]. As these technological advancements progress, they lay the foundation for a sustainable transportation ecosystem that promises significant environmental and health improvements [13].

Colombia's strategic approach to fostering electric mobility extends beyond urban electrification, targeting comprehensive regulatory reforms and infrastructural developments [14], [15]. These initiatives, while part of a larger global shift towards sustainable transportation, underscore Colombia's unique position in leveraging policy and technology to facilitate EV adoption [5], [16]. The national strategy includes not only the introduction of electric buses but also the development of an extensive network of charging stations and incentives for private EV buyers, showcasing a multi-faceted approach to reducing transportation emissions [17].

The emphasis on regulatory frameworks and financial incentives illustrates the government's commitment to overcoming the traditional barriers to EV adoption. Such measures include significant reductions in import tariffs for EVs and financial support for local governments to update their public transportation fleets [6]. This policy-driven momentum is critical in accelerating the transition to electric mobility, reflecting a model that could inspire similar initiatives in other developing countries [18]. Additionally, Colombia's investment in renewable energy sources for powering its EV infrastructure signals a forward-thinking approach to ensure the sustainability of its electric mobility ecosystem [19], [20].

EVs provide substantial environmental advantages over traditional diesel vehicles [21]. They play a crucial role in reducing greenhouse gas emissions, which are a significant contributor to climate change [22]. EVs also improve urban air quality by significantly lowering pollutant emissions like nitrogen oxides and particulate matter, which are common in diesel exhaust [23]. This reduction in air pollutants is particularly important in urban areas, where traffic congestion often leads to poor air quality [24]. Furthermore, the shift to EVs is aligned with global efforts to transition to cleaner energy sources, as they can be powered by renewable energy, further reducing their overall environmental impact. This transition is essential in our pursuit of sustainable transportation and urban development, contributing to a healthier environment and public health.

The adoption of EVs in sustainable transportation encounters significant challenges, including high initial costs that deter consumer adoption despite potential long-term savings on fuel and maintenance, and environmental and logistical issues related to EV battery disposal and recycling [25], [26]. Moreover, the scarcity of comprehensive charging infrastructures, especially in rural and underserved areas, stands as a considerable obstacle [27]. Addressing these hurdles necessitates a collaborative approach among governments, industries, and communities to forge cost-effective, environmentally sustainable solutions and widespread charging networks [28]. Colombia exemplifies this collaborative spirit, leading in sustainable mobility within Latin America through initiatives that blend global best practices with local strategies, thereby enhancing environmental and public health outcomes [7]. The country's progress underscores the importance of continuous innovation and international collaboration in advancing electric mobility and achieving global environmental goals.

Despite significant advancements in EV technology and policy initiatives, several critical challenges remain unaddressed, hindering the global transition to sustainable transportation. Our research aims to tackle these unresolved issues by developing innovative solutions for the efficient integration of EVs into existing urban infrastructures and enhancing the environmental sustainability of EV adoption. By focusing on the optimization of charging infrastructure and proposing novel approaches to battery technology and recycling, this study contributes to overcoming the economic and logistical barriers currently impeding the widespread adoption of EVs. Through a detailed analysis of these challenges and the presentation of actionable solutions, our work seeks to advance the field of electric mobility, offering a roadmap for future research and policy-making in sustainable transportation.

## 2. PROBLEM STATEMENT

The global environmental and health challenges posed by diesel transportation are increasingly pressing [1]. Diesel engines, particularly those used in urban public transport, are a major source of black carbon emissions, significantly contributing to air pollution and associated health risks. These emissions, prevalent in densely populated urban areas, have been linked to a range of respiratory and cardiovascular diseases, underscoring the urgency for effective mitigation strategies. The impact of diesel emissions extends beyond public health, affecting overall air quality and contributing to environmental degradation. This situation demands prompt and effective action, highlighting the need for sustainable alternatives and stricter environmental policies to address the growing concerns related to diesel transportation.

Colombia's response to the environmental challenges posed by traditional transportation methods has led to significant policy changes, particularly in the adoption of EVs in urban settings [5], [6]. The introduction of electric buses in the capital city, Bogotá, serves as a prime example of these efforts. This initiative represents a major step towards reducing greenhouse gas emissions, a crucial factor in combating climate change. It also signifies a shift towards sustainable urban mobility, offering a cleaner and more environmentally friendly alternative to conventional diesel-powered buses. By implementing such policies, Colombia is not only addressing local environmental and health concerns but also contributing to global efforts to reduce the impact of transportation on the environment.

EVs stand at the forefront of addressing the environmental issues posed by traditional transportation methods [19]. They offer a greener alternative, significantly reducing greenhouse gas emissions and airborne pollutants compared to their diesel counterparts. This reduction is particularly vital in urban areas, where traffic congestion and vehicle emissions greatly impact air quality and public health. The transition to electric mobility is, therefore, a critical component in tackling the challenges of urban pollution and climate change. By embracing EVs, we can move towards a more sustainable and environmentally friendly transportation system, benefiting both the planet and future generations.

The path to widespread adoption of EVs is beset with several challenges that need to be overcome. The high initial purchase costs of EVs pose a significant barrier for many potential buyers, despite the long-term economic and environmental benefits [25]. Another major obstacle is the limited availability of charging infrastructure, which is crucial for the practicality and convenience of using EVs. Concerns about the efficiency, lifespan, and environmental impact of EV batteries also need to be addressed. These issues are critical not just for consumer acceptance but for the overall success and sustainability of the EV market. Addressing these challenges is essential for realizing the full potential of EVs in reducing environmental pollution and transitioning to a cleaner future.

## 3. METHOD

This study aims to develop a comprehensive simulation model for an EV battery charger, focusing on its interaction with the public power grid. Our objectives include researching the operational conditions and charging strategies of EV chargers, designing a power conversion and control scheme based on these findings, evaluating the performance of the model under various conditions, and documenting the development and outcomes for publication. This endeavor will enhance our understanding of EV charging systems and their integration into power grids.

### 3.1. Background information

#### 3.1.1. Charging process considerations

EV charging technologies have evolved to include plug-in, pantograph, and induction systems, each offering unique benefits and challenges. Plug-in charging, the cornerstone of current EV infrastructure, spans from slow, residential charging to faster, more sophisticated systems that support efficient energy transfer and communication between the vehicle and charger. These systems, by adjusting charging parameters like current and voltage, enhance battery longevity and charging convenience. Pantograph charging, tailored for public transportation like electric buses, enables quick energy top-ups at stops, crucial for maintaining service efficiency. This method, however, demands substantial infrastructure investments to integrate mechanical arms and charging stations within urban transit networks.

Induction charging stands out as a wireless, innovative approach, leveraging electromagnetic fields to transfer power without direct contact, thereby simplifying the charging process and minimizing wear. Despite its advantages, the widespread adoption of induction charging faces hurdles, including high installation costs and the need for significant modifications to urban infrastructure. Each charging technology presents distinct operational modes and infrastructural requirements, necessitating a deep understanding for effective implementation across diverse settings. The strategic deployment of these systems is imperative, considering their power specifications, environmental impacts, and the goal of seamless integration into existing and future urban landscapes.

These charging technologies underline the importance of adapting infrastructure and policies to support the varied needs of EV charging. As the prevalence of EVs grows, understanding and optimizing these charging processes become central to achieving a sustainable, efficient transportation ecosystem. The choice among these technologies involves balancing cost, convenience, and environmental considerations, pointing toward a future where charging infrastructure is as diverse as the vehicles it supports.

#### 3.1.2. Charging stations

When planning EV charging stations, critical considerations include charger quantity to meet demand, influenced by local EV prevalence and traffic volume, and spatial layout to facilitate easy vehicle access and maneuvering. Space design varies by location, requiring compatibility with public areas, service stations, or residential garages, and must consider electrical infrastructure's capacity to handle the load. Strategic charger placement and clear signage enhance usability, while safety and compliance with electrical standards are paramount. Decisions between underground and aerial wiring balance aesthetics, cost, and technical feasibility, with security measures ensuring user and equipment safety. Addressing grid impacts involves staggered charging and renewable energy integration to manage demand and minimize environmental effects, requiring innovative grid adaptations and smart technologies for sustainable EV charging solutions.

#### 3.1.3. Environmental impact

The environmental impact of electomobility, particularly when comparing EVs to internal combustion engine vehicles, is a multifaceted issue. EVs offer significant advantages in terms of greenhouse gas emissions, as they produce zero direct emissions, unlike their gasoline counterparts which emit CO2, NOx, and particulate matter. However, the overall environmental footprint of EVs heavily depends on the electricity source used for charging. If this electricity is derived from renewable sources, the impact is substantially lessened. Additionally, EVs contribute to a notable reduction in local air pollution, a significant benefit in urban settings. The production of EV batteries, predominantly lithium-ion, involves extracting minerals like lithium, cobalt, and nickel, which can have environmental implications. Efforts are underway to develop more sustainable and recyclable batteries to mitigate these impacts. The end-of-life management of these batteries, including recycling, is crucial for minimizing environmental harm. Moreover, the construction of charging infrastructure also consumes resources but typically has a smaller environmental footprint than maintaining a network of fossil fuel stations. Lastly, the widespread adoption of EVs could increase electricity demand, impacting generation and distribution infrastructure, potentially accelerating the shift towards renewable energy sources.

Exploring the environmental impact of transportation electrification in Latin America and Colombia reveals unique challenges and opportunities. The adoption of EVs significantly reduces local emissions, improving air quality, particularly in densely populated urban areas. The impact of EVs on greenhouse gas emissions in the region depends on the electricity generation mix, which varies widely across Latin America. Rich in mineral resources, Latin America plays a crucial role in the global supply chain for battery production. Sustainable mining practices and efficient battery recycling and management are essential to minimize environmental harm. The expansion of EV charging infrastructure requires careful planning and resource allocation. Effective policies and regulatory frameworks are vital to support sustainable electromobility, balancing environmental benefits with the socio-economic realities of the region.

#### 3.1.4. Risks and maintenance

EVs face both common and unique risks, including traffic accidents, battery fires due to damage or overheating, and electrical safety hazards. These risks necessitate advanced cooling systems and careful handling, especially during high-powered charging to mitigate overheating and electrical dangers. Maintenance focuses on battery care to extend its life, advocating for specific charging habits and regular system checks, including the regenerative braking system and fluid levels. Despite EVs having fewer fluid-related maintenance needs than combustion vehicles, attention to coolant and brake fluids, alongside safety training for handling high-voltage components, is essential for safe and efficient operation.

#### 3.1.5. Applicable regulations

The global and Colombian regulatory frameworks for EV charging stations integrate standards like EN 61851 and EN 62196, along with national regulations such as RETIE and NTC 2050, to ensure the safety, efficiency, and environmental compliance of electrical installations. These regulations cover everything from general conductive charging system requirements to specific guidelines for DC charging stations, connectors, and noise pollution control. In Colombia, additional standards focus on material selection, grounding systems, and installation locations to promote sustainable transportation. Collectively, these guidelines form a comprehensive regulatory base that supports the development of safe, interoperable, and environmentally friendly EV charging infrastructure, reflecting a global commitment to advancing electric mobility.

### 3.2. Design

The performance analysis of an EV charging station is conducted through three detailed design stages. The basic design stage establishes the general electrical connection scheme for the EV charger, laying the groundwork for the system's framework. Next, the detailed design stage delves into the specifics, such as the exact plant layout and the intricacies of electrical control and power schemes, ensuring all components are optimally arranged and controlled. The final stage, performance design, involves a more complex setup, featuring a double busbar configuration tailored for a station capable of supporting ten chargers. This stage focuses on efficiency and the ability to handle high-capacity charging requirements.

#### 3.2.1. Basic design considerations

The design process begins with a thorough evaluation of the VOLVO 7900 electric bus model, examining its technical specifications to understand the requirements for its charging system (Table 1). Based on these specifications, a standard topological configuration for a unidirectional AC/DC charger is proposed. This configuration is in accordance with IEC 61851-1 and IEC 61851-22 standards, which dictate key parameters such as nominal power, input and output voltage ranges, operating frequency, and switching frequency. The design also considers the nominal current requirements, ensuring the charger can efficiently and safely deliver power to the vehicle's battery system.

Table 1. Compilation of technical data VOLVO 7900 electric bus

| Electric motor | |
|---|---|
| Parameter | Factory value |
| Motor | |
| Max. output (KW) | R85 max. 200 |
| Maximum wheel torque (Nm) | 19000 |
| Energy storage system (ESS) | |
| Battery capacity | 94 kWh |
| Voltage | 600 V |
| Maximum charging power (CCS DC/AC) | 150 kW |
| Maximum charging power (OppCharge) | 300 kW |
| Total power capacity | 198, 264 o 330 kWh |

Based on the technical data and in line with the requirements of charging stations to directly supply energy to batteries, a standard topological configuration for a unidirectional AC/DC charger is proposed, adhering to IEC 61851-1 and IEC 61851-22 standards. This configuration includes a nominal power of 2×22 kW, a nominal input voltage of 400 VAC, and an adjustable nominal output voltage ranging from 10 to 1000 VDC, set at 800 VDC for this application. Additionally, the charger operates at a frequency of 60 Hz with a switching frequency of 10 kHz and supports a nominal current range of 6 to 63 A. This will be governed according to the standard configuration provided by IEC 61851, as shown in Figure 1.

The basic electrical schematic for an EV charger is comprehensive, encompassing several crucial components. It includes a power source tailored to handle the high energy demands of EVs. The vehicle connector and connection cable are designed for robustness and compatibility with various EV models. A user interface is integrated for ease of interaction, while the control unit acts as the system's brain, ensuring efficient power management. Safety protections are paramount, guarding against electrical hazards. The charger also incorporates meters and sensors for monitoring, communication devices for connectivity, a grounding system for additional safety, and an energy meter to track electricity usage. This schematic adheres to relevant regulations, ensuring the charging process is both safe and efficient (Figure 2).

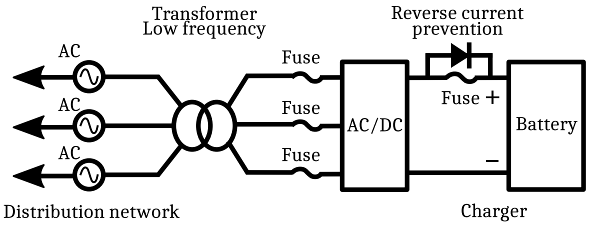



Figure 1. Typical configuration of a charger according to IEC 61851 standard

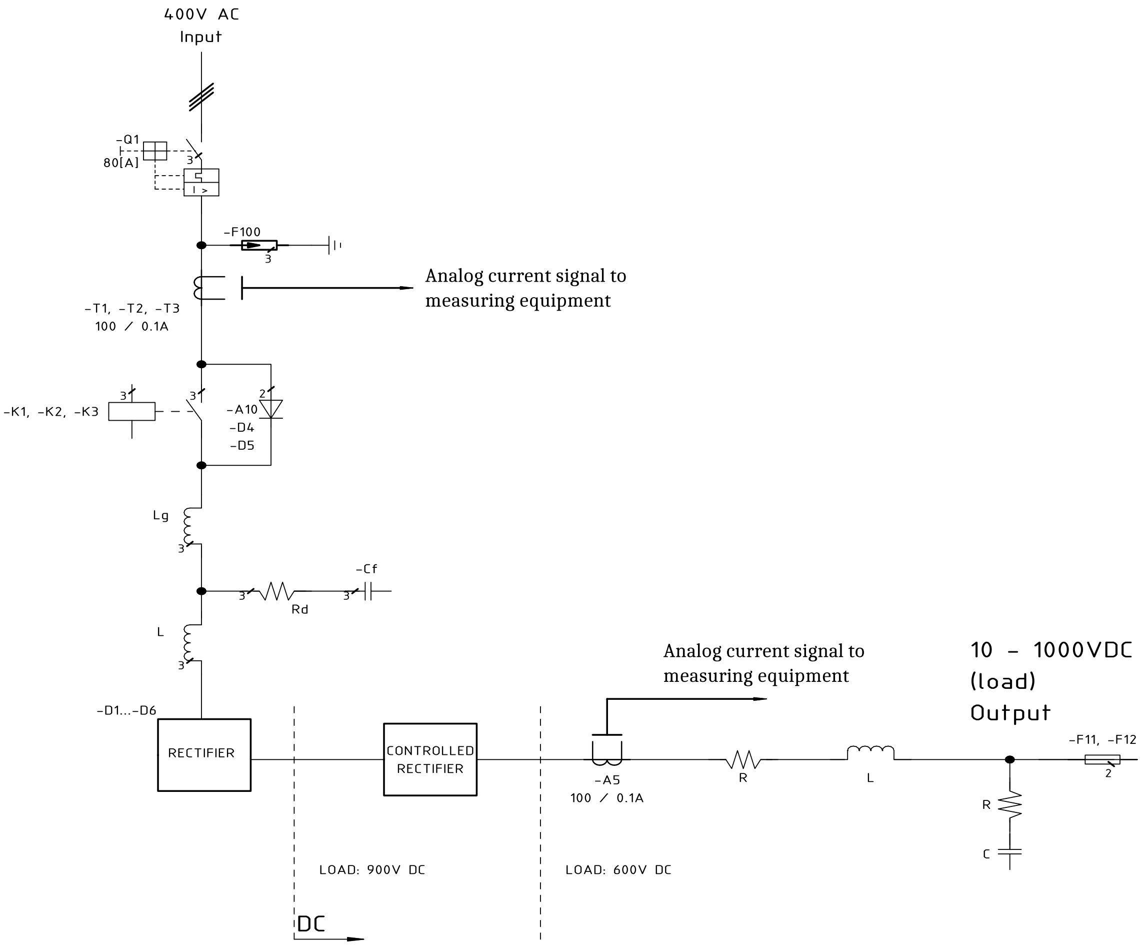



Figure 2. Basic wiring diagram for EV charger

### 3.2.2. Detailed design

In the detailed design phase for a charging station, it's crucial to meticulously plan the electrical control and power schemes, as well as the physical layout. This process involves creating detailed plans and drawings to accurately depict the system's design. Technical specifications are vital to ensure all components meet the required performance criteria. The assembly of components must consider tolerances for precision and reliability. Ergonomic and usability aspects are essential to create a user-friendly interface. Lastly, strict adherence to relevant norms and standards guarantees the safety, efficiency, and compliance of the charging station with industry regulations.

The control design for an EV charger comprises four stages, each integral to maintaining consistent representation of the currents and voltages from the external power grid. These stages involve capturing three-phase current and voltage signals, a challenging aspect due to the sinusoidal nature of these signals. To simplify the control process, MATLAB transformation blocks, specifically Clark and Park transformations, are employed. These transformations convert the variable system into a more manageable constant representation. This process is crucial for the effective management of power flow, ensuring that the charger operates efficiently and reliably under varying grid conditions.

The *abc to* $\alpha\beta$ block utilizes the Clarke transformation (also known as the alpha-beta transformation), which converts a three-phase abc system into an orthogonal two-phase $\alpha\beta$ system, assuming a balanced system. The input signals of the balanced three-phase system with rms values are determined by the following equations:

$$V_a = 400 \cdot \cos(\omega t)[V]$$
$$V_b = 400 \cdot \cos(\omega t + 120^\circ)[V]$$
$$V_c = 400 \cdot \cos(\omega t - 120^\circ)[V]$$

Based on these measurements, the aim is to input and apply them in the conversion matrix of the Clarke transformation. The matrix is defined as (1):

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{1}$$

The result is a linear transformation converting the variables $a$, $b$, and $c$ into two variables named alpha ($\alpha$) and beta ($\beta$). These alpha-beta coordinates are perpendicular to each other and are rotated 120 degrees with respect to the $a$, $b$, $c$ coordinates, simplifying the analysis and control of three-phase systems. The *abc* to *dq* block utilizes the Park transformation to represent a three-phase *abc* system in a synchronous rotating *dq* system, where *d* is direct axis component and *q* is quadrature axis component.

Although the number of variables to control has been simplified, they still have a sinusoidal nature. Therefore, the Park transformation (also known as rotational transformation) is essential. It extends the Clarke transformation, simplifying the analysis of electric machines. The transformation uses alpha-beta variables (fixed coordinates in space) to convert them into dqo coordinates (rotating coordinates) using the Park transformation matrix:

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} \tag{2}$$

Here, $d$ and $q$ are the new coordinates in the rotating (dqo) system, $\alpha$ and $\beta$ are the alpha-beta coordinates in the fixed system, and $\theta$ is the rotation angle. The dqo coordinates are particularly useful in control as they simplify the representation of electrical and mechanical variables in the charger's reference system, facilitating direct control of magnetic flux, and improving the system's efficiency and performance.

In the PI control strategy for the EV charger, the proportional-pntegral (PI) approach is implemented to address the proportional (P) and integral (I) errors which may arise due to a battery's poor condition. The proportional error (P) indicates the immediate discrepancy between the system's output and the desired reference level. In the context of the EV charger, it reflects the difference between the current and desired battery charge levels, adjusting the charging current to match the desired level. The integral error (I) captures the cumulative discrepancy over time. This error is crucial for long-term charge current adjustments, ensuring the battery eventually reaches the desired charge level.

The choice of the PI control strategy is crucial for correcting errors caused by batteries in poor or mediocre condition. When a damaged battery fails to retain charge correctly, the charger might attempt to supply more current than necessary, leading to overcharging. Such overcharging can result in dangerous overheating of the battery and, in extreme scenarios, chemical leaks or explosions. Finally, using the output from the PI controllers, pulse width modulation (PWM) control is implemented. This controls the activation and deactivation sequence of the IGBTs to produce the DC voltage signal at the output of the AC/DC converter. The AC/DC converter's primary objective is to transform the three-phase AC input signal into a DC output signal. This is achieved using insulated gate bipolar transistors (IGBTs), which modulate the PWM to control the output.

In the EV charger control system, the transfer function plays a crucial role in frequency domain analysis. It essentially maps the relationship between the input and output of the system, specifically representing the conversion of three-phase AC input voltage to DC output for battery charging. This function is key to understanding how the system responds to varying input frequencies. It provides insights into the stability and efficiency of the charger's response, vital for optimizing performance. Using MATLAB to determine this function allows for a thorough analysis and fine-tuning of the system, ensuring optimal charging behavior under various electrical conditions (Figure 3).

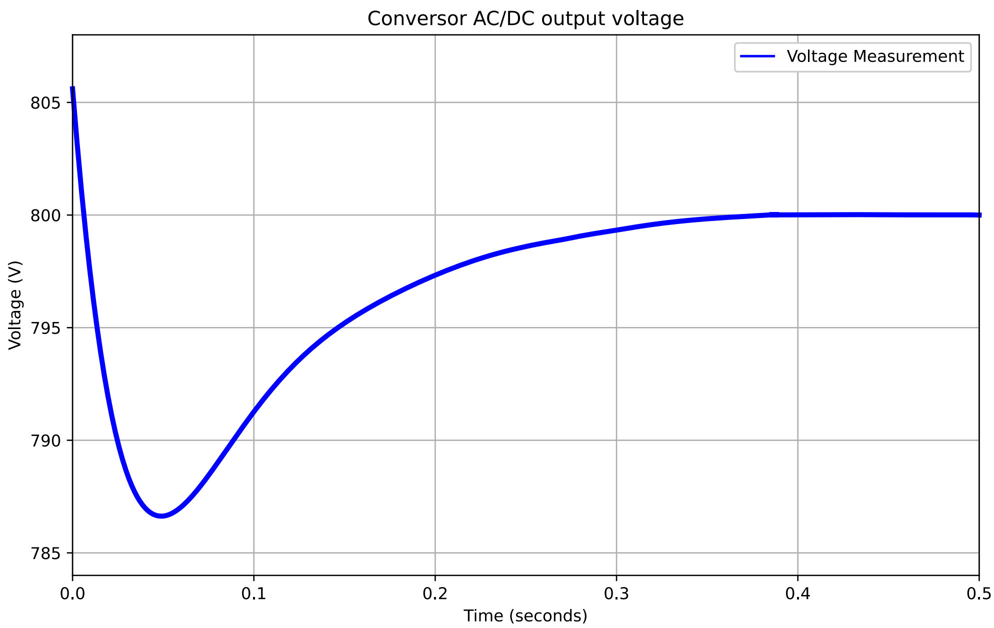



Figure 3. Conversor AC/DC output voltage

The calibration of a PI controller within an EV charger's control system is a meticulous process that hinges on the precise determination of the proportional (*Kp*) and integral (*Ki*) constants. This procedure begins with the acquisition of output voltage data from a three-phase rectifier bridge, which is essential for understanding the dynamic behavior of the charger under various load conditions. Utilizing MATLAB's scope tool, this data is carefully logged and exported to the MATLAB workspace, enabling a detailed analysis of the system's performance. The *estimate process data* feature within MATLAB then plays a pivotal role, as it allows for the extrapolation of the system's output model from the captured data, ensuring that the constants are tuned to accurately reflect the charger's operational parameters. Ultimately, the PI controller's transfer function is defined using the command `G=tf(P1)`, a critical step that encapsulates the controller's response characteristics and is vital for ensuring optimal charger performance and battery longevity. The transfer function obtained for the system is as (3):

$$P1\,(s) = \frac{2696}{1 \times 10^{-6}s + 1} \tag{3}$$

As the culmination of these four stages, the following schematic as seen from MATLAB Simulink is obtained, depicted in Figure 4.

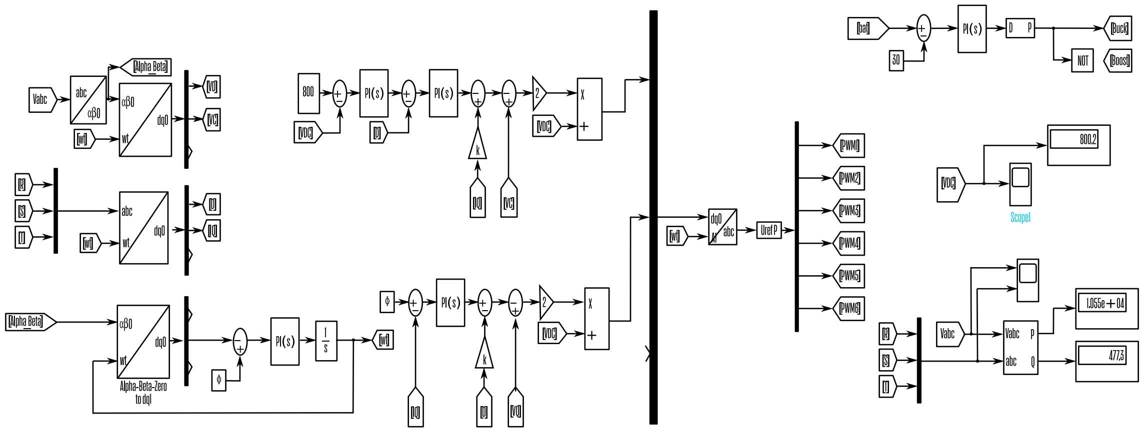



Figure 4. Control circuit simulation

In the design of the charging station's power system, as depicted in Figure 1, from the rectifier bridge filter stage to the EV battery, the filter is meticulously engineered to comply with IEC/EN 61000-2-2 standards, ensuring maximum harmonic current distortion does not exceed 10% and voltage harmonic distortion remains below 5%. This adherence to standards involves the calculation of total harmonic distortion of current (THD(I)) as a percentage of the harmonic currents' effective value in relation to the fundamental current's effective value, with the micrologic E control unit calculating THD up to the fifteenth harmonic:

$$THD(I) = \frac{\sqrt{\sum_{n=2}^{15} I_n^2}}{I_1} \tag{4}$$

The THD percentage in current may exceed 100%. The THD(I) provides an evaluation of the current waveform distortion with a single number. Table 2 shows the limit values of THD(I).

Table 2. Percentage of THD in current according to IEC/EN 61000-2-2

| THD(I) value | Comments |
|---|---|
| THD(I)≤10% | Weak harmonic currents: low risk of operational failures. |
| 5%<THD(I)≤50% | Significant harmonic currents: risk of heating, oversizing of sources. |
| 50%<THD(I) | Very important harmonic currents: almost certain risk of operational failures, degradation, and dangerous heating unless the installation has been calculated and sized considering these restrictions. |

The THD of voltage (THD(U)) is defined according to the IEC/EN 61000-2-2 standard as a percentage of the effective value of harmonic voltages of orders greater than 1 in relation to the effective value of the fundamental voltage. The micrologic E control unit calculates the THD(U) up to the fifteenth harmonic:

$$THD(U) = \frac{\sqrt{\sum_{n=2}^{15} U_n^2}}{U_1} \tag{5}$$

The THD percentage in voltage can exceed 100%, but in practice rarely surpasses 15%. The THD voltage (THD(V)) provides an evaluation of the voltage waveform distortion with a single number. The following limit values are typically assessed by energy distributors: Table 3 shows the limit values of THD(V).

Table 3. Percentage of THD in voltage according to IEC/EN 61000-2-2

| THD(V) value | Comments |
|---|---|
| THD(V)≤5% | Insignificant voltage waveform distortion: low risk of operational failures. |
| 5%<THD(V)≤8% | Significant voltage waveform distortion: risk of heating and operational failures. |
| 8%<THD(V) | Significant voltage waveform distortion: high risk of operational failures unless the installation has been calculated and sized for this level of distortion. |

Furthermore, the design will comply with the IEC 61000-3-4 standard, which establishes permissible values for nominal voltage variation (± 2%) and frequency variation (± 0.5%). With the aforementioned parameters in mind, the detailed design for the power circuit is initiated considering that a power converter through high-frequency switching action converts alternating current to direct current or vice versa safely, quickly, and efficiently. The power converter integrated Skiip is composed of IGBT insulated gate transistors, Skiip type antiparallel diodes (613 GD123–3DVL V3) with the following characteristics: i) reverse polarization voltage 1200 VAC; ii) nominal current 444 A; and iii) maximum switching frequency 15 kHz.

The high-frequency switching capability of the power converter decreases as the temperature increases. Considering that the charging station will be installed in Bogotá D.C. with an average temperature of 25 °C, and as seen in the equipment's technical sheet, it operates under normal conditions up to approximately 50 °C.

Next, we calculate the coupling capacitor at the output of the rectifier:

$$C \geq \frac{T_{SW}}{2 \cdot \Delta V_{CC}} \cdot I_{CC} \cdot \left(1 - \frac{\sqrt{3}}{2} \cdot m_a\right) \tag{6}$$

Where $T_{SW}$ is the switching frequency period, $\Delta V_{CC}$ is the desired voltage ripple on the DC bus, $m_a$ is the modulation index at nominal power of the rectifier, and $I_{CC}$ is the average current at the DC output, dependent on the power and voltage handled at the DC output. The variation $\Delta I_{fase}$ is the maximum desired variation in line current.

Obtaining:

$$T_{SW} = \frac{1}{f_{SW}} \tag{7}$$

$$\Delta V_{CC} = 1\% \cdot V_n \tag{8}$$

of the direct current bus, with $\Delta V_{CC} = 8V$ for a nominal voltage of 800 VDC.

To calculate the modulation index ($m_a$) the following equation is used:

$$V_{FF_{RMS}} = \frac{\sqrt{3}}{2 \cdot \sqrt{2}} \cdot m_a \cdot V_{CC} \tag{9}$$

Given that $V_{CC} = V_{In} = 800$ [VDC] and that $V_{FF_{RMS}} = 400$ [VAC], we obtain:

$$m_a = \frac{2 \cdot \sqrt{2} \cdot V_{ff}}{\sqrt{3} \cdot V_{cc}} \tag{10}$$

Now, according to the apparent power and nominal input voltage, we have:

$$I_{CC} = \frac{P[KW]}{V_{CC}[V]} \tag{11}$$

Therefore, the coupling capacitor is:

$$C \geq \frac{T_{SW}}{2 \cdot \Delta V_{CC}} \cdot I_{CC} \cdot \left(1 - \frac{\sqrt{3}}{2} \cdot m_a\right) \tag{12}$$

The coupling capacitor C is installed on the direct current bus. In the project, a capacitor of 500 µF was implemented. Lastly, to complete the LCL filter, the damping resistances Rd are required to reduce the resonance effect in the filter, which are calculated as (13):

$$Rd = \frac{1}{3} \cdot \frac{1}{2\pi \cdot f_o \cdot C} \tag{13}$$

Taking into account the commercial values of resistance, the resistance implemented in the filter Rd is 100 mΩ. The parasitic inductances inherent to power electronic systems can cause voltage spikes above the maximum tolerable by equipment. Considering this, the manufacturer of the power converter recommends connecting capacitors of 0.47 µF. With the parameters identified, the power system is configured in MATLAB

Simulink, as shown in Figure 5. This configuration in Simulink enables an accurate simulation of the charging station's power dynamics, incorporating the detailed specifications of the power converter and associated components.

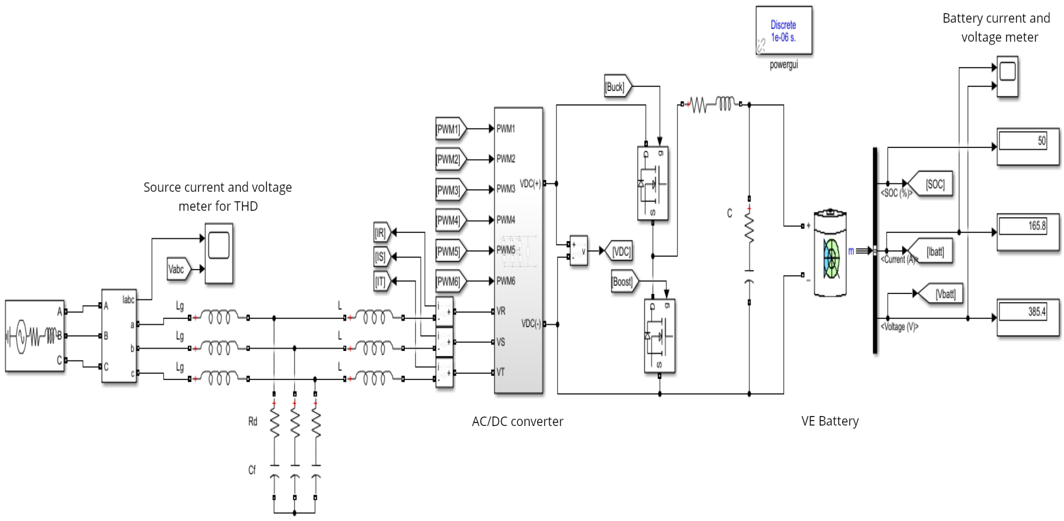



Figure 5. Control circuit simulation

In the detailed design phase of the charging station, crucial factors such as electrical power/control schematics and plant layout are developed. These designs reflect the unique requirements of the location and are based on the insights gained from the research. For our purpose of evaluating the performance of an EV charger from the electrical supply network's perspective, several real-world conditions are considered. The designed electric charging station has an installed capacity of approximately 0.5 MW to accommodate 10 chargers, catering to 10 Volvo 7900 electric buses within an area of about 6000 square meters. The infrastructure layout, as shown in Figure 6, includes 10 charging stations, each with parking space for two buses, an AC distribution board, transformer room, and a control room for auxiliary services and communications.

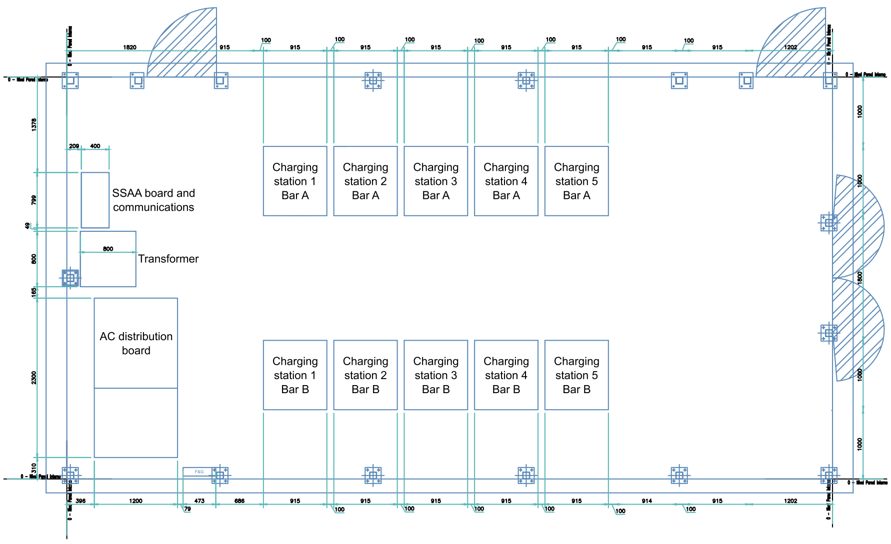



Figure 6. Infrastructure layout for EV charging station, 6000 square meters

Moving to the performance design, the station's parameters are defined for both medium and low voltage networks. For medium voltage, the nominal voltage is 34.5 kV with a maximum DC current of 0.167 kA, among other specifications listed in Table 1. The low voltage network, detailed in Tables 4 and 5, operates at a nominal voltage of 400 V with a system frequency of 60 Hz. The design also considers operational modes, with the chosen configuration being a double busbar with coupling. This configuration enhances control, protection, and maintenance of the electrical network. The substation's detailed single-line diagrams, as shown in Figures 7 and 8, provide an in-depth view of the electrical system, depicting the chosen configuration, possible commercial references for each piece of equipment, and a specific schematic of the nominal short-circuit current that each conductor, bar, and circuit component might encounter.

Table 4. Medium voltage network parameters

| Medium voltage | |
|---|---|
| Nominal voltage | 34.5 kV |
| Maximum DC current | 0.167 [kA] |
| Voltage operation reference point | 100 |
| Max tension factor c | 1.1 |
| Min tension factor c | 1 |
| Neutral type in installation | Low resistance |

Table 5. Low voltage network parameters

| Low voltage | |
|---|---|
| Nominal voltage | 400 V |
| Network system | TN-S |
| System frequency | 60 Hz |
| Tolerable contact voltage | 50 V |
| Ambient temperature of devices | 30 °C |
| Max tension factor c | 1.1 |
| Min tension factor c | 0.9 |
| Max permitted voltage drop in network | 3% |

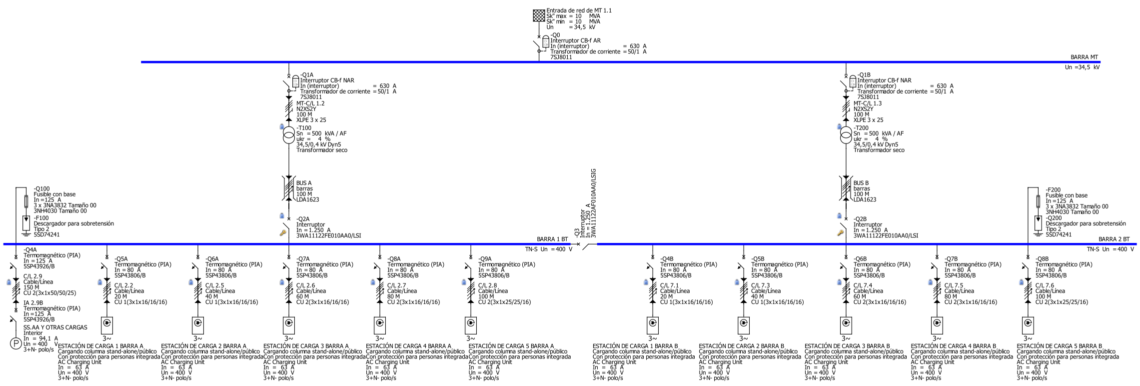


Figure 7. Single-line diagram-equipment parameters

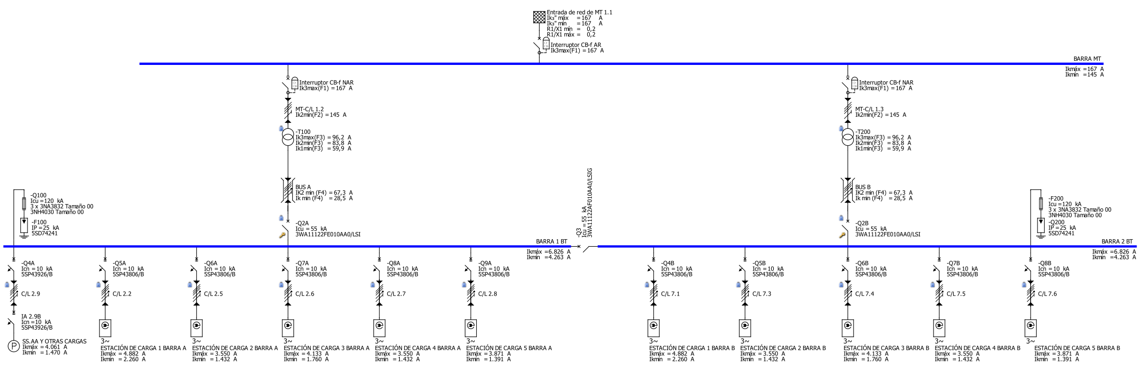


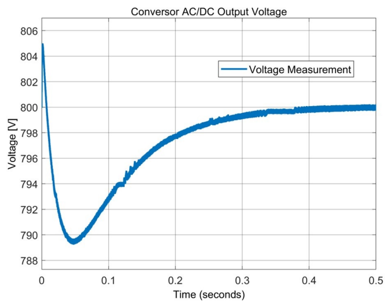
Figure 8. Single-line diagram-short circuit current load

## 4. RESULT AND DISCUSSION

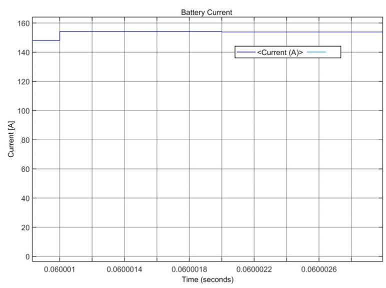
The analysis and simulations across two distinct software environments, Simulink® and MATLAB® for control systems, and SIMARIS® for electrical installations, reveal critical insights into the performance and efficiency of EV charging systems. This discussion juxtaposes our findings with existing studies to underscore advancements, challenges, and future implications in the field of sustainable transportation.

### 4.1. Simulink® and MATLAB®

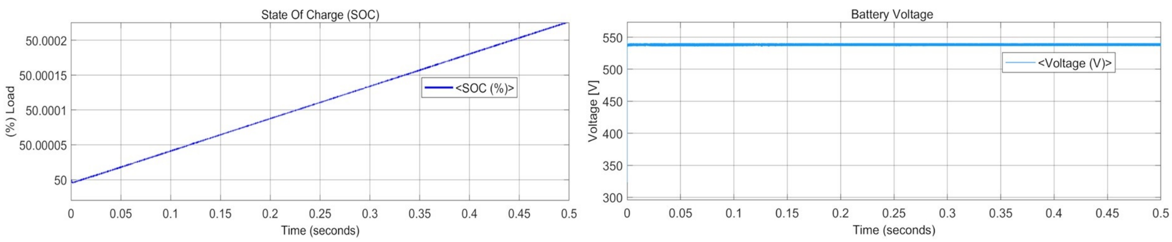
Evaluating system performance through Simulink® and MATLAB® provided a comprehensive understanding of the control aspects and energy delivery mechanisms to the EV battery. The obtained transfer function and assessment of THD underscore the system's efficiency in energy conversion and harmonic mitigation, compared to existing models. Figure 9 illustrates various aspects of the battery charging process, which is vital for understanding the efficiency and safety of power systems. Figure 9(a) of the figure displays the voltage output signal from the AC/DC converter, highlighting the stability and fluctuations within the conversion process which are critical for optimal battery charging. Figure 9(b) focuses on the behavior of the current flowing into the battery, providing insights into the charge acceptance and the impact of charge rate on battery health. Finally, Figure 9(c) shows the behavior of the battery charging voltage, depicting how the voltage evolves throughout the charging cycle. This part is essential for assessing the effectiveness of the charging protocol and ensuring that the voltage levels do not exceed the battery's specifications, which could lead to damage or reduced lifespan.




(a)




(b)




(c)

Figure 9. Battery charging process: (a) voltage output signal from the AC/DC converter, (b) battery current behavior, and (c) battery charging voltage behavior

#### 4.1.1. Critical discussion on transfer function and total harmonic distortion

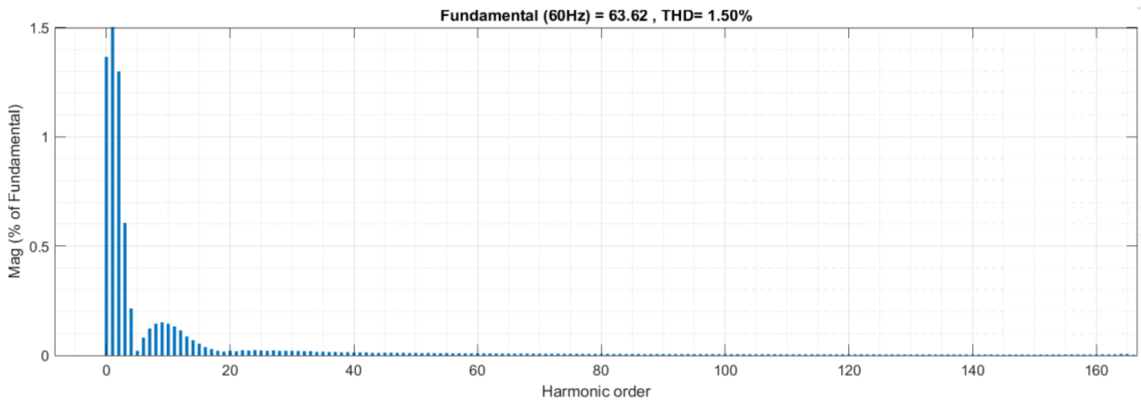
The transfer function derived:

$$G = \frac{2696}{1X10^{-6} \cdot S + 1} \tag{14}$$

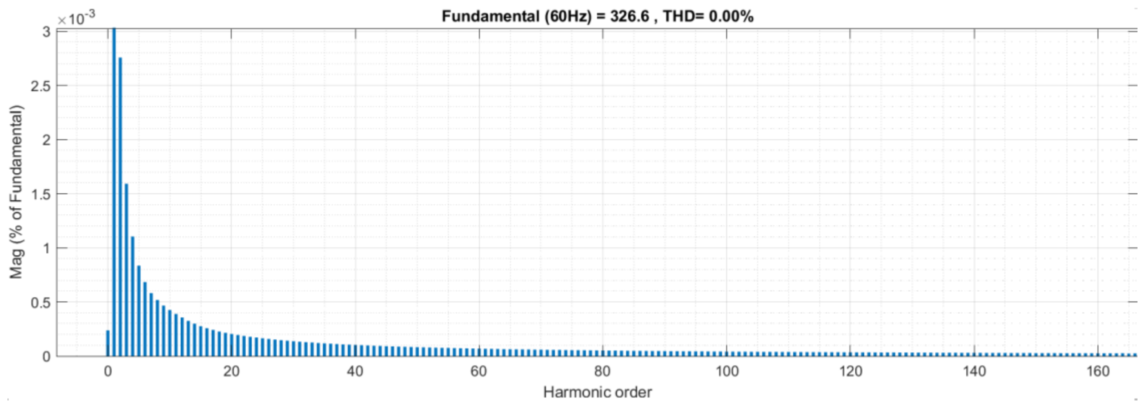
and the system's response to a step input highlight the EV charger control system's dynamic stability and efficiency. When contrasted with literature, our system demonstrates superior performance with optimized *Kp* and *Ki* values, ensuring minimal deviation in control response and enhancing charge efficiency. The THD analysis further reveals the system's efficacy in maintaining power quality, with THD values not exceeding the standard limits, illustrating a significant improvement over conventional systems.

#### 4.1.2. Implications and future research directions

Our findings indicate that the proposed control strategy and harmonic mitigation techniques could significantly enhance EV charging station efficiency and reliability. Future research could explore the integration of renewable energy sources into the charging network to further reduce carbon emissions and operational costs. Additionally, advancing battery technology to complement our control strategies could address range anxiety and charging time concerns, pivotal for accelerating EV adoption. Figure 10 provides a detailed analysis of the THD in the power system, focusing on the harmonic components that significantly impact system performance. Figure 10(a) presents the THD related to the first order harmonic (THD I), illustrating its magnitude and how it contributes to the overall distortion in the current waveform. This component is crucial for evaluating the fundamental frequency interference in the system. Figure 10(b) examines the THD related to the fifth order harmonic (THD V), detailing its influence on the voltage waveform.




(a)




(b)

Figure 10. The resultant THD: (a) THD I order harmonic and (b) THD V order harmonic

### 4.2. SIMARIS®

The use of SIMARIS® allowed for the detailed planning of electrical installations, contributing to the optimization of the EV charging station's design. The load flow analysis and electrical component selection underscore the potential for efficient power distribution and consumption.

#### 4.2.1. Comparison with existing infrastructure planning tools

Our method, utilizing SIMARIS®, represents a significant advancement over traditional infrastructure planning tools in the design of EV charging stations. This approach not only streamlines the planning process but also incorporates precise load flow analytics, ensuring minimal impact on the electrical grid. Our findings highlight the superiority of SIMARIS® in facilitating sustainable and efficient power management, establishing a new industry standard for the development of electric mobility infrastructure. By leveraging this innovative tool, we can achieve a more resilient and adaptable charging network that aligns with future mobility demands and environmental sustainability objectives, setting a precedent for next-generation infrastructure planning. Figures 11 and 12 provide a comprehensive overview of an electrical system's performance through unifilar diagrams, each focusing on different aspects of system analysis. Figure 11 details the load flow analysis of the system. This figure visually represents the path and magnitude of electrical power through various components, such as transformers, lines, and loads, providing crucial insights into voltage drops, current flows, and power losses within the network. Figure 12 complements the previous figure by focusing on the energy usage and efficiency within the same electrical system. This figure encapsulates the energy consumption, generation, and possible losses in a graphical format that allows for an easy assessment of energy performance.

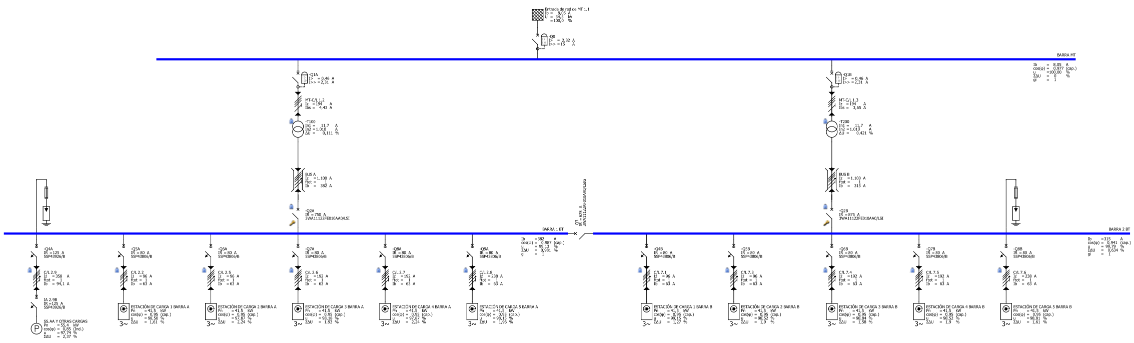


Figure 11. Unifilar-load flow

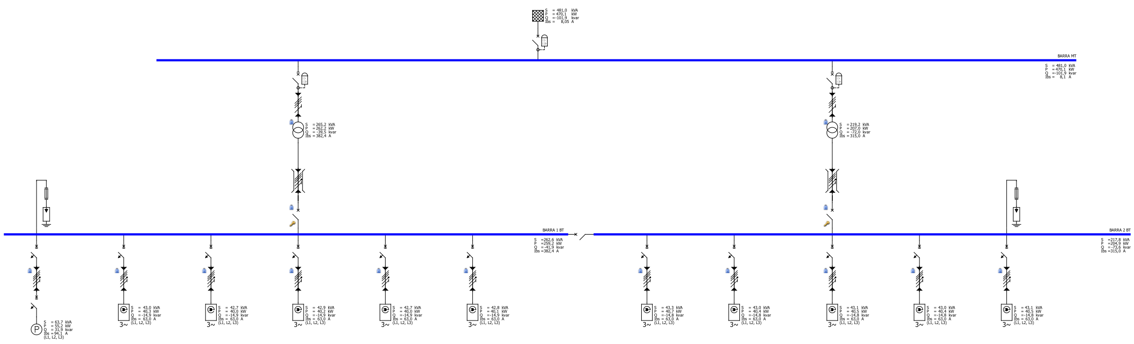


Figure 12. Unifilar-energy report

#### 4.2.2. Implications for infrastructure development and policy

Our research offers critical insights into the development and optimization of EV charging infrastructure, serving as a strategic guide for policymakers, urban planners, and industry stakeholders. It underscores the necessity for advanced planning tools and collaborative strategies that align with technological advancements and sustainability goals. These findings advocate for evidence-based policy-making to support the scalable expansion of electric mobility, emphasizing the integration of renewable energy sources and smart grid technologies to enhance the efficiency and reliability of EV charging stations. By facilitating a multi-stakeholder dialogue, this study aims to catalyze the formulation of adaptive policies and standards that promote the widespread adoption of EVs. Such initiatives are vital for achieving global sustainability targets, reducing carbon emissions, and fostering a resilient urban transportation ecosystem. The proactive engagement of government authorities in creating favorable regulatory environments and incentives can accelerate this transition, ensuring that the infrastructure development keeps pace with future demands for electric mobility.

## 5. CONCLUSION

This study has extensively explored the intricacies and challenges associated with the design, implementation, and analysis of EV charging stations. Through meticulous research and simulation, we have delved into various facets of EV charging infrastructure, ranging from the technical nuances of charger design to the broader implications on power grids and environmental impact. One of the primary conclusions drawn from this research is the critical importance of careful planning and design in the establishment of EV charging stations. The intricate balance between electrical demands, infrastructure limitations, and environmental considerations is a key factor in the successful deployment of EV charging networks. Our findings underscore the need for adherence to international standards such as IEC 61851-1 and IEC 61851-22 to ensure safety, reliability, and efficiency in charger operations.

Moreover, the analysis of the electrical network's interaction with EV charging stations revealed significant insights. The impact of resistive, capacitive, and inductive loads on the electrical grid was thoroughly examined, highlighting the need for staggered charging and advanced load management to mitigate potential grid overloads. The adoption of renewable energy sources and smart charging systems emerged as vital strategies to balance the growing demand for EV charging with existing grid capacities and environmental goals. Our simulations in MATLAB and Simulink provided valuable data on the system's performance, particularly in terms of transfer function behavior and THD. The results indicated that with appropriate filtering and control mechanisms, the electrical disturbances to the grid could be minimized, thereby enhancing the overall efficiency and stability of the charging process.

Additionally, the environmental analysis revealed that while EVs offer significant reductions in greenhouse gas emissions compared to internal combustion engine vehicles, challenges remain in the realms of battery production and end-of-life management. Sustainable practices in resource extraction, battery manufacturing, and recycling are essential to fully realize the environmental benefits of electromobility. The transition to EVs presents a complex but manageable challenge that requires a multidisciplinary approach encompassing electrical engineering, environmental science, and infrastructure planning. Our study provides a comprehensive framework for understanding and addressing these challenges, paving the way for a more sustainable and efficient future in transportation.

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## BIOGRAPHIES OF AUTHORS

**William Fabián Sánchez Díaz** is a final semester student of Electrical Engineering at the Universidad Distrital Francisco José de Caldas (Colombia), actively engaged in research with the ARMOS research group (modern architectures for power systems). His areas of expertise include electrical power grid analysis and modeling of electrical systems. He is currently involved in several projects that aim to innovate and improve the efficiency of electrical systems and electric vehicle technology. He can be contacted at email: wfsanchezd@udistrital.edu.co.

**Jonatan Tolosa Vargas** is a final semester student of Electrical Engineering at the Universidad Distrital Francisco José de Caldas (Colombia). As a dedicated researcher in the ARMOS research group (modern architectures for power systems), he has contributed significantly to the fields of electrical power grid, modeling of electrical systems, and electric vehicles. His academic pursuits and research focus on exploring innovative solutions and methodologies within these areas. He can be contacted at email: jtolosav@udistrital.edu.co.

**Fredy Martínez** is a professor specializing in control, intelligent systems, and robotics at the Universidad Distrital Francisco José de Caldas (Colombia). He also holds the esteemed position of director of the ARMOS research group (modern architectures for power systems). His academic expertise and research dedication are evident in his work on control schemes for autonomous robots, mathematical modeling, electronic instrumentation, pattern recognition, and multi-agent systems. Dr. Martínez earned his Ph.D. in Computer and Systems Engineering from the Universidad Nacional de Colombia, showcasing his deep commitment to advancing the field. He can be contacted at email: fhmartinezs@udistrital.edu.co.