

## Elektrikli Araçlar için Şarj Doğrultucu Devrelerinin Harmonik Değerlendirmesi

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### ÖZ

Elektrikli araç (EA) şarj istasyonlarında güç kalitesinin artırılması ve toplam harmonik bozulma (THB) değerlerinin azaltılması, özellikle hızlı şarj uygulamaları açısından kritik öneme sahiptir. Şebekeden temin edilen alternatif akımı (AA), batarya sistemleri için doğru akıma (DA) dönüştüren EA şarj cihazları; Mod 1, Mod 2 ve hızlı DA şarj gibi farklı şarj modlarına bağlı olarak çeşitli doğrultucu topolojileri içermektedir. Bu çalışmada, ilave filtreleme bileşenlerine ihtiyaç duymaksızın düşük harmonik bozulma sağlayan yenilikçi bir 12 darbeli doğrultucu topolojisi önerilmektedir. Önerilen yapı, geleneksel tek fazlı ve üç fazlı altı darbeli doğrultucularla; harmonik performansı, güç faktörü ve verimlilik açısından karşılaştırılmalı olarak değerlendirilmiştir. Elde edilen sonuçlar, filtre devresi kullanılmasa bile 12 darbeli doğrultucunun şebekeden çekilen akımda yaklaşık %20 düzeyinde düşük THB sağladığını ve bu sayede daha temiz ve verimli bir güç aktarımı sunduğunu ortaya koymaktadır. Bu bağlamda önerilen topoloji, yüksek güç ve gerilim seviyelerinde çalışan EA hızlı şarj istasyonları için uygulanabilir ve sürdürülebilir bir çözüm sunmaktadır.

### Harmonic Evaluation of Electric Vehicle Charging Rectifier Circuits

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#### ABSTRACT

Improving power quality and reducing total harmonic distortion (THD) are of critical importance in electric vehicle (EV) charging stations, particularly for fast-charging applications. EV chargers, which convert alternating current (AC) from the grid into direct current (DC) for battery charging, incorporate various rectifier topologies depending on the selected charging modes (Mode 1, Mode 2, and fast DC charging). This study proposes an innovative 12-pulse rectifier topology that achieves low harmonic distortion without the need for additional filtering components. The proposed configuration is evaluated in comparison with conventional single-phase and three-phase six-pulse rectifiers in terms of harmonic performance, power factor, and efficiency. The results demonstrate that the 12-pulse rectifier achieves a significantly lower THD in the grid current, approximately 20%, even without filter circuits, contributing to a cleaner and more efficient power supply. Therefore, the proposed topology presents a viable and sustainable solution for high-power and high-voltage EV fast-charging stations.

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## 1. Introduction

With transportation towards sustainability and carbon neutrality at the forefront, EVs are rapidly becoming widespread as a more environmentally friendly alternative to fossil fuel vehicles. The increasing number of EVs has brought about the necessity of developing charging infrastructure. EV charging stations are required to establish the connection between the grid and the vehicles.

Rechargeable battery systems are central to the functionality of EVs, which rely on efficient and reliable charging infrastructure (Sharma et al., 2022). EV chargers are designed to convert alternating current (AC) from the grid into direct current (DC), which is suitable for charging batteries. Different rectifier circuits facilitate this conversion depending on the charging mode, such as Mode 1, Mode 2, or fast DC charging.

Power electronic converters in charging processes can cause various harmonic distortions on the electrical grid. Harmonics are generated in the charger due to non-linear operating characteristics. Due to these harmonics, power quality deterioration and voltage instability occur (Yilmaz et al., 2013). Selecting the proper charging method is an important aspect to consider when charging. EV chargers are classified into three levels based on voltage level and their power rating, as shown in Table 1. Most EV charging can be accomplished overnight in residential settings using a standard 120V output Level 1, the slowest charging option. 240 V output Level 2 charging is commonly found in homes, workplaces, and public charging stations, and is faster than Level 1 charging. Single-phase solutions typically employ levels 1 and 2. For three-phase solutions, Level 3 DC fast charging is designed for public charging stations and commercial applications like fuel stations (Saraswathi and Ramachandran, 2024).

**Table 1.** Classification of chargers according to levels

EV Charger Level	Voltage Level	Grid Supply
Level 1	120/230 $V_{ac}$	Single-phase
Level 2	240/400 $V_{ac}$	Single-phase or three-phase
Level 3	208/600 $V_{ac}$	Three-phase

When conventional rectifier topologies, including single-phase and three-phase rectifiers, are examined comprehensively, they differ in terms of their harmonic effects on the grid. Single-phase rectifiers are commonly used in low-power applications but suffer from high THD and poor power factor. Three-phase rectifiers improve power quality but still require additional filtering methods to comply with power quality standards such as IEEE 519 (Committee et al., 2014). Previous studies have explored active and passive filters, phase-shifting transformers, and multi-pulse rectifiers as potential solutions to harmonic distortion.

Single-phase bidirectional rectifier (SPBR) is used in EV battery charging to focus on analyzing switching sequences to evaluate power losses, which aids in component sizing and efficiency. A prototype with 10 kW output power was developed, achieving a peak efficiency of 97.5%, unity power factor, and THD of less than 7% during full power operation (Esteve et al., 2024). Senol et al., (2025) show that harmonic distortion tends to increase as the charging current decreases during the charging of

eight popular EV models. In addition, THD can reach up to 25% in the worst cases, and some vehicles can exceed individual harmonic limits. A single-phase, five-level power factor correction (PFC) rectifier for EV battery charging is proposed in (Tiwari et al., 2024). The proposed topology provides capacitor voltage balance by a complementary switching method, reduces voltage stress on the switches, and eliminates the need for an additional DC filter. Experimental results show that the proposed rectifier provides 93.8% efficiency at 230 V input voltage and 2 kW output power and offers high power quality using fewer components compared to conventional multi-level and single-level rectifier topologies. (Pratama et al., 2024) analyzes harmonic distortion in EV charging Stations and proposes a shunt active power filter using a Phase-Locked-Loop to mitigate harmonics, reducing THD and Total demand distortion (TDD). The result of THD and TDD, before applying the filter, the THD and TDD values were 18.69% and 12.52%, respectively, which decreased to 1.32% and 0.85% after the filter was applied. The operating principle of a three-phase uncontrolled rectifier charger with passive power factor correction and the development of its frequency-domain harmonic analytical model have been analyzed in Wenxiong et al., (2016). Based on simulation and experimental results, the model accurately predicts the harmonic content of the charging current under different power levels and filter inductor conditions, with improved accuracy when the DC filter inductor  $L_f$  is less than 14.3 mH. (Bi et al., 2023) introduces a control strategy for a single/three-phase EV charging system, which can be reconfigured to operate as a single-phase rectifier. The application of this method is in EV charging systems, where it combines deadbeat prediction current control (DPCC) with a modified repetitive control (RC) to enhance performance and stability, especially under grid voltage disturbances. The results demonstrate improved reliability and efficiency, validated by a 7.4 kW single-phase AC-DC converter prototype, which confirms the method's effectiveness.

A new hybrid approach is proposed to improve the harmonic mitigation capability of a 12-pulse diode bridge rectifier (DBR) for fast EV battery charging applications (Dubey et al., 2022a). This study aimed to reduce the size and complexity of the system by using a diode rectifier supported by a clamp circuit with only two active switches and a weak DC interconnect film capacitor. In addition, a zigzag-configured high-frequency solid-state transformer improves the grid-side current quality by blocking zero sequences. (Lan et al., 2022) investigated a 100-kW EV fast charger that integrates a 12-pulse rectifier with two buck-type DC-DC converters, utilizing a triangular current shaping method to enhance current harmonics performance. The system was designed for high-power applications, offering simplicity in operation with a low active semiconductor count, and this approach achieved high efficiency (98.73%), low THD (1.36%), and a near-unity power factor (0.999) while maintaining a wide output voltage range. To demonstrate that the use of EVs increased harmonic distortion in the electrical grid, leading to power losses and reduced efficiency, a charging system utilizing a Shunt Active Power Filter (SAPF) was developed (Neupane et al., 2024), reducing THD from 56.3% to 1% while improving power quality. The system employed a Buck-Boost converter and a Constant Current Constant Voltage (CCCV) charging scheme to ensure a stable charging process.

In this literature review, rectifiers have been extensively studied for their effectiveness in harmonic reduction. While 6-pulse and 12-pulse rectifiers require minimal filtering, 6-pulse rectifiers have been widely used but generate significant low-order harmonics (Hu et al., 2022), necessitating external filters. In contrast, 12-pulse rectifiers have demonstrated promising results in harmonic mitigation by canceling lower-order harmonics through phase shifting, thereby enhancing overall power quality. However, existing research has primarily focused on 12-pulse rectifiers in conjunction with filtering techniques rather than evaluating their standalone performance in EV charging applications.

This paper presents a 12-pulse rectifier without a filter for EV charging stations designed to minimize the THD value without additional filtering components. The proposed topology is evaluated by comparing the conventional single-phase and three-phase rectifiers in terms of harmonic performance, power factor, and efficiency. The results indicate that the 12-pulse rectifier without a filter significantly reduces harmonic distortion, making it a promising solution for enhancing the power quality of EV charging stations.

The contributions of this study can be summarized as follows:

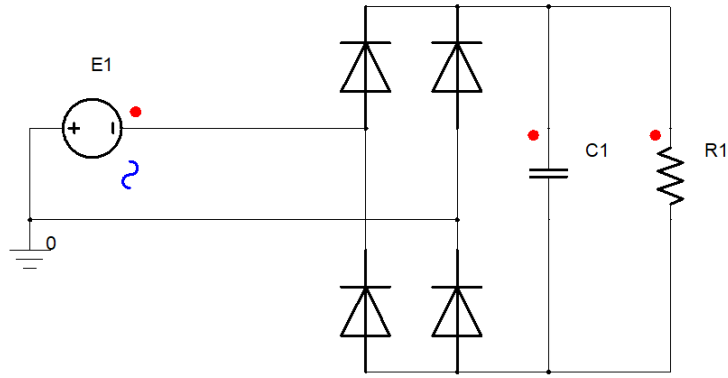
- Performance of a 12-Pulse Rectifier with Low THD for Fast Charging Stations of EVs
- Improving Power Quality by Reducing Harmonic Components in Currents Without Using Filter Circuits
- Proposal of a 12-Pulse Rectifier for High Power and Voltage Levels

## **2. Material and Methods**

This section describes the topologies of various Rectifier Circuit Models for electric vehicle (EV) charging applications and explains the model and details of the 12-pulse Rectifier Circuit model made in the Ansys/Twin Builder simulation application.

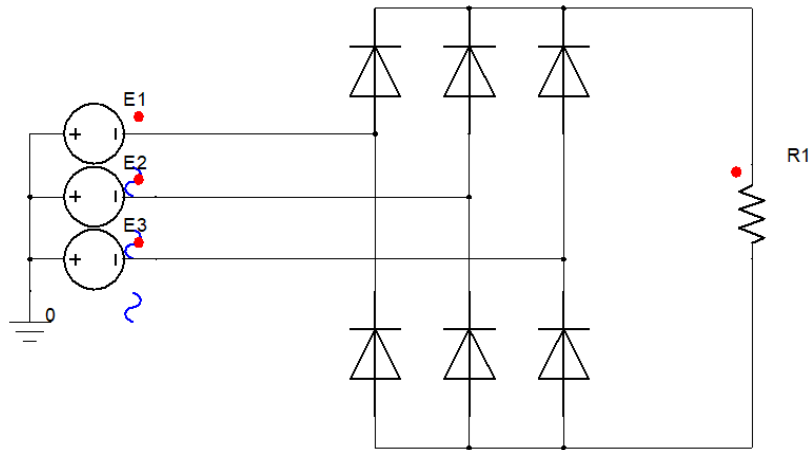
### *2.1. Rectifier Circuit Models*

As shown in Figure 1, single-phase rectifier circuits are essential components in electrical systems, converting alternating current (AC) to direct current (DC) for various applications. These circuits are widely used in power supplies for electronic devices, electric vehicle chargers, and other DC-powered equipment (Gou, 2023). EV Level 1 charging units, connected to the single-phase city grid, are classified as slow charging modes. All loads employing such a single-phase rectifier circuit draw significant harmonic current components.



**Figure 1.** Single-phase rectifier circuit

Figure 2 shows the conventional diode rectifier and full-bridge DC-DC converter, which can reduce the DC link voltage from the AC grid voltage. The diode rectifier generates the DC link voltage, and then the full-bridge DC-DC converter reduces the DC voltage level (Wai et al., 2019; Lee et al., 2020). This rectifier is simple to operate since it does not use active switches and does not require any gate drivers or control systems. Diode rectifiers can add 40–70% THD to the grid currents, which causes stress on the grid. Due to low efficiency, unidirectional power flow, and high THD, the traditional passive rectifier topology is not recommended for fast-charging applications. The lower-order harmonics ( $5^{th}$ ,  $7^{th}$ ,  $11^{th}$ , and  $13^{th}$ ) have high amplitudes (Zhaksylyk et al., 2023; Seleem et al., 2024).

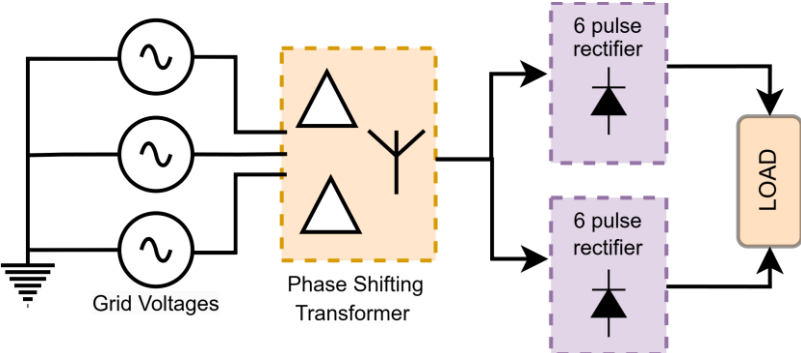


**Figure 2.** Three-phase rectifier circuit

Compared with the six-pulse rectifier, the multi-pulse rectifier produces fewer harmonics, and, therefore, the recommended rectifier type for DC fast charging units is a 12-pulse rectifier circuit with shifted phases. In a traditional approach to DC fast charging of EVs, a three-phase uncontrolled diode bridge rectifier followed by an isolated DC-DC converter is directly connected to the grid. However, this involves low-order harmonics, resulting in poor power factor and power quality (Abdollahi, 2022).

Figure 3 shows the topology of a 12-pulse rectifier proposed for EV DC fast battery charging. A phase shift transformer with a  $\Delta/\Delta$ -Y connection provides the required 30-degree phase shift between each

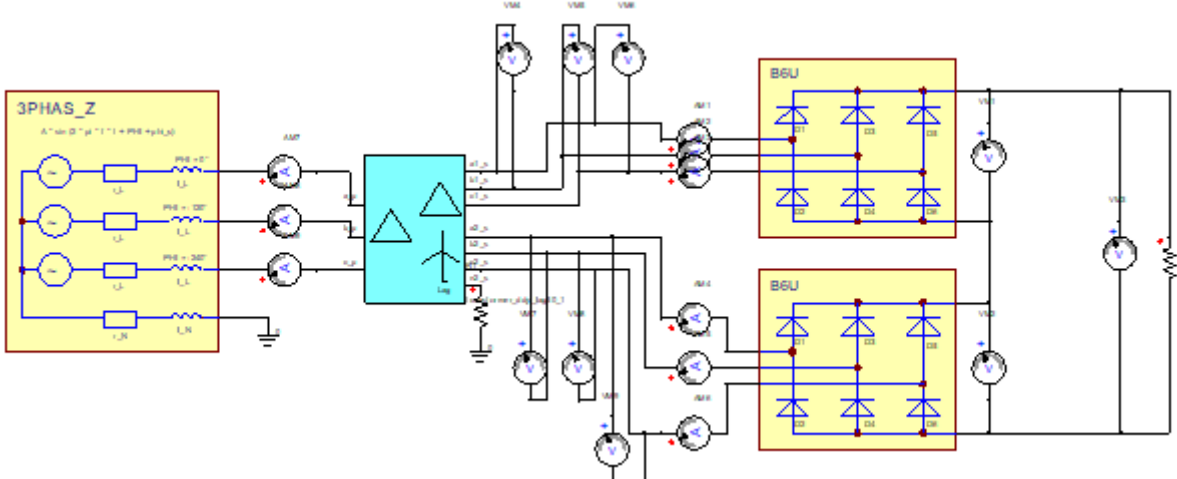
phase voltage provided for the upper and lower diode bridges and uses current and voltage control to control the output current of the two diode bridges separately (Dubey et al., 2022b).



**Figure 3.** The connection schematic diagram of a 12-pulse rectifier

**2.2. ANSYS Modeling of Rectifier Circuits**

The circuit diagram of the proposed rectifier used for simulation in ANSYS-Twin Builder is shown in Figure 4. As stated, it consists of an autotransformer that produces two three-phase voltage sets with 12 pulses and a 30° phase shift to provide DC voltage to the EV charging circuit. A 12-pulse phase-shifting rectifier circuit is designed. Compared to traditional 6-pulse rectifier circuits, the 12-pulse structure provides lower THD and better power quality, increasing grid compatibility. This structure, obtained by using a phase-shifting transformer, increases the efficiency of the system by reducing the need for filters thanks to its low harmonic components. The designed rectifier circuit provides a more uniform current drawn from the grid while producing a stable DC voltage at the output. The simulations show that the proposed topology improves the power factor and complies with IEEE 519 harmonic standards.



**Figure 4.** DC charge 12 pulse rectifier circuit

**3. Results and Discussions**

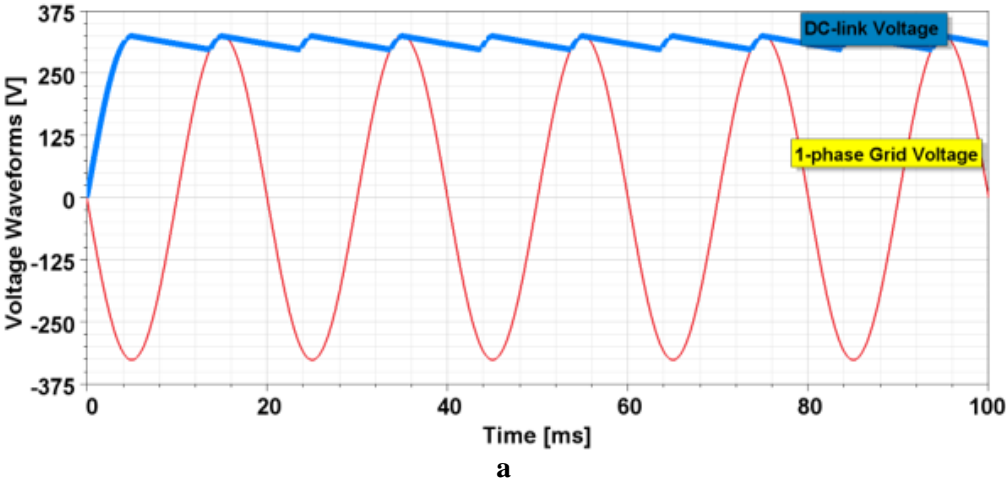
The DC-link voltage waveform shown in Figure 5a indicates that the rectifier output exhibits a notable ripple component, an inherent characteristic of single-phase rectification. This ripple arises due to the

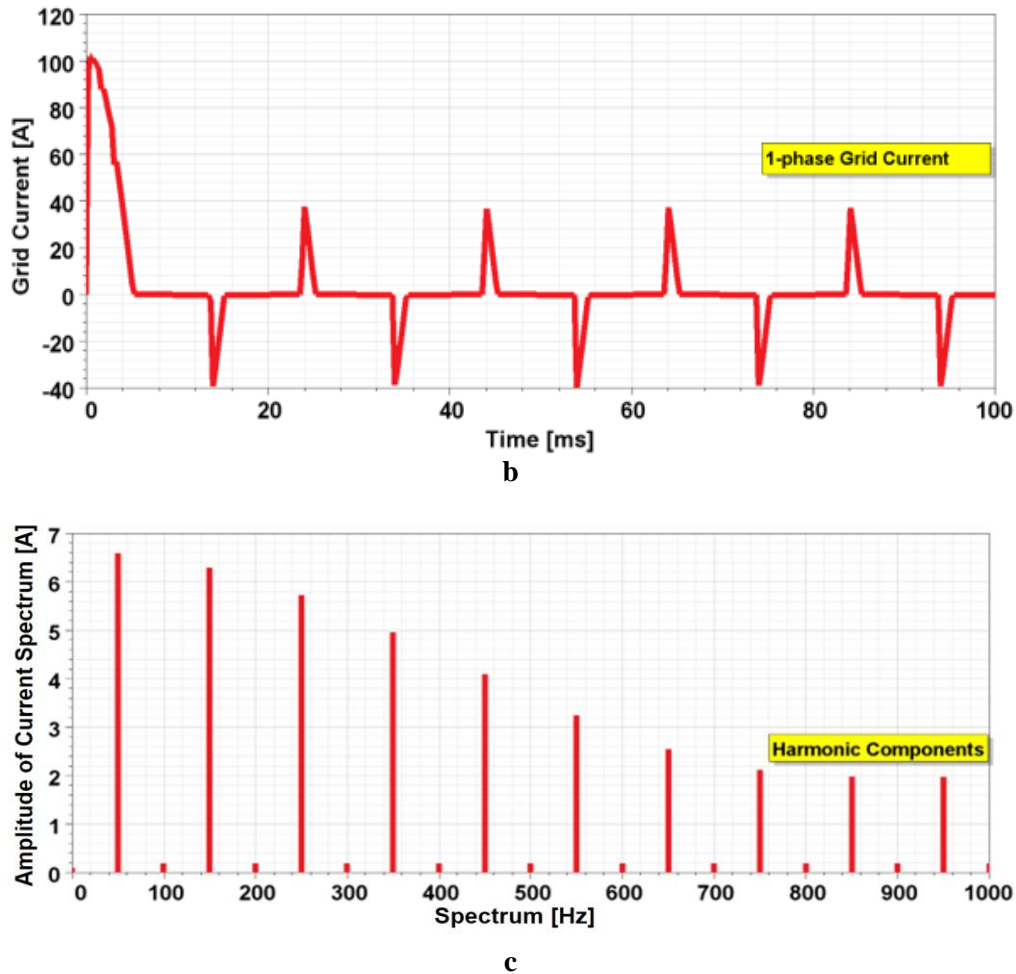
cyclic nature of the input voltage and the absence of an ideal smoothing mechanism. Since EV batteries require a stable and ripple-free DC voltage for efficient charging and prolonged battery lifespan, additional filtering circuits or DC-DC converters are necessary to mitigate these fluctuations. Excessive voltage ripple can adversely affect the overall efficiency of the charging system.

The grid current waveform presented in Figure 5b reveals that the single-phase rectifier draws current with a high harmonic content, which degrades the power quality of the grid. Additionally, the abrupt variations in the waveform can lead to electromagnetic interference (EMI) issues, potentially necessitating the implementation of power factor correction (PFC) circuits or other mitigation techniques to ensure compliance with power quality standards.

The harmonic spectrum analysis illustrated in Figure 5c confirms the presence of significant harmonic components, particularly at the 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, and higher-order frequencies. The high THD observed in the grid current further underscores the negative impact of the single-phase rectifier on power quality. Excessive harmonic injections into the grid can result in voltage distortion, increased reactive power demand, and potential resonance issues, which can impair the stability and efficiency of the power distribution system.

Single-phase rectifier circuits inherently draw excessive harmonic currents due to their reliance on a filter capacitor to reduce the DC-link voltage ripple. This filtering requirement is the primary factor contributing to the presence of substantial harmonic content in the grid current. Notably, harmonics at all integer multiples of 3 are present, and the THD value exceeds 80%, highlighting the significant distortion introduced by the rectification process.

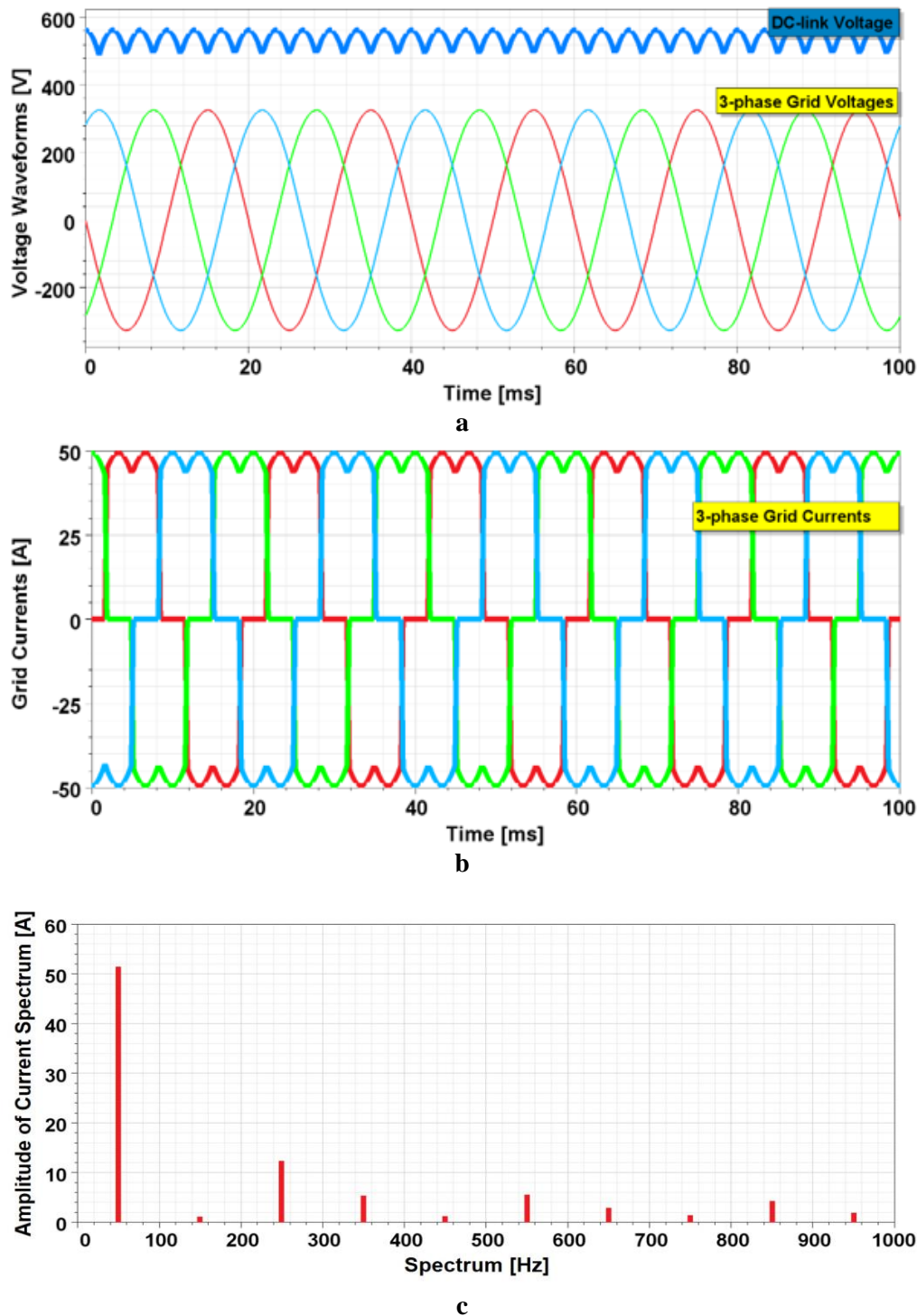




**Figure 5.** A single-phase rectifier, a) DC output voltage waveform, b) current waveform drawn from the grid, c) grid current harmonic spectrum

The DC-link voltage waveform shown in Figure 6a exhibits a periodic ripple, which is an inherent characteristic of a six-pulse rectifier. Although the voltage appears relatively stable, the presence of ripple results from the rectification process and the absence of an ideal filtering circuit. This voltage ripple can impact the efficiency of connected loads, such as EV chargers, and may necessitate additional filtering to ensure a more stable DC-link voltage.

The grid current waveforms presented in Figure 6b indicate that the rectifier draws current in a non-sinusoidal manner, introducing harmonic components due to the switching behavior of the rectifier. While a three-phase rectifier inherently provides a better current balance compared to a single-phase rectifier, harmonic distortion remains a concern. These harmonics can negatively affect power quality, requiring mitigation techniques such as passive filtering or active power factor correction (PFC) to comply with power quality standards.



**Figure 6.** Three-phase 6-pulse rectifier, a) DC output voltage waveform, b) current waveform drawn from the grid, c) grid current harmonic spectrum

The harmonic spectrum depicted in Figure 6c confirms the presence of significant harmonic components, particularly at the 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup>, and 13<sup>th</sup> harmonics, which are characteristic of six-pulse rectification. The presence of these harmonic components increases THD, leading to power quality deterioration, increased losses in grid components, and potential resonance issues.

Compared to a single-phase rectifier circuit, a three-phase six-pulse rectifier inherently draws lower harmonic current components from the grid (Kul et al., 2024). Specifically, 3<sup>rd</sup> and multiples of 3

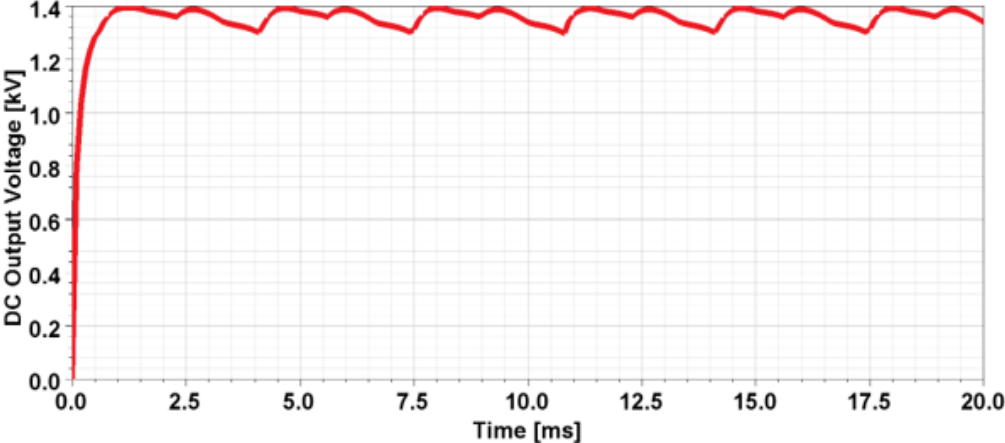
harmonic currents are eliminated, resulting in a THD level approximately 20% lower and a reduced DC-link voltage ripple, even in the absence of a filter capacitor. Furthermore, Level-4 DC fast charging systems, which are widely used in high-power EV charging stations, can effectively operate with six-pulse rectifiers at power levels of up to 300 kW, making them a viable solution for high-power applications (Arena et al., 2024; Ilahi et al., 2024).

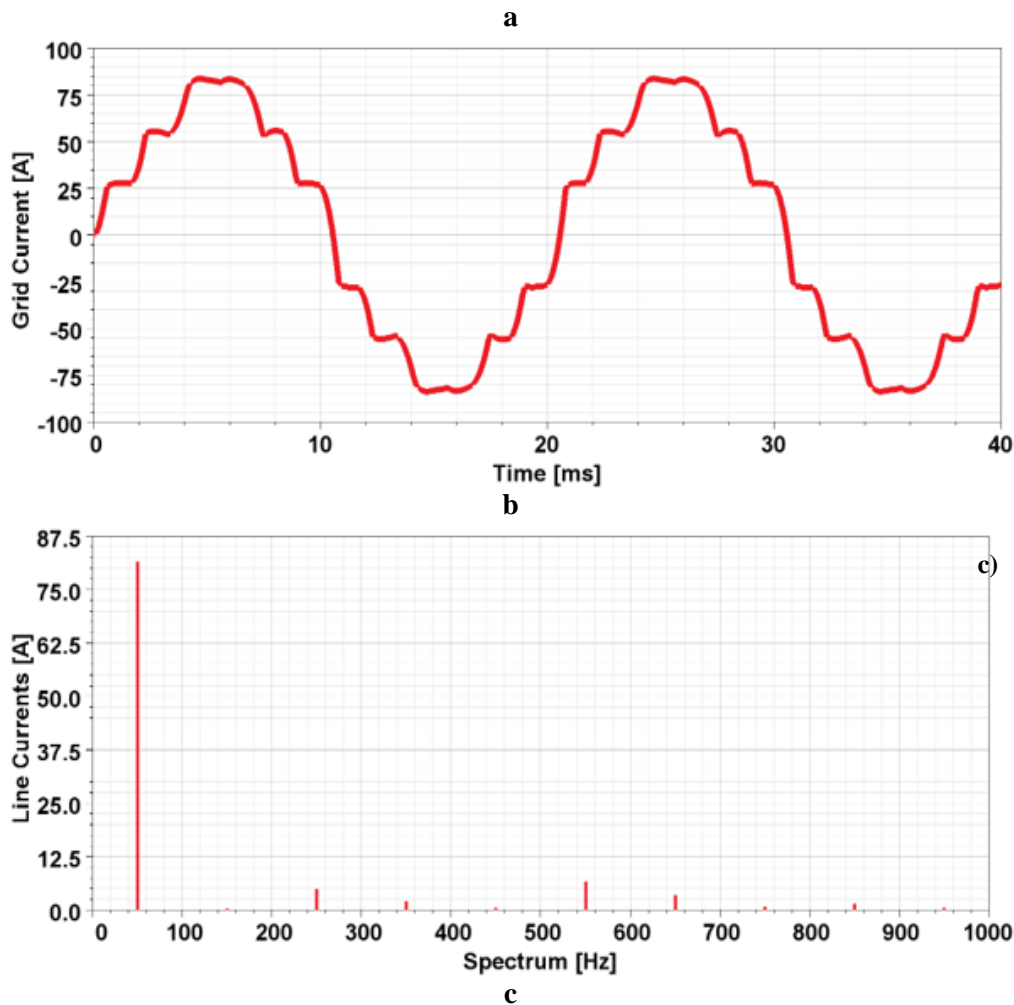
The DC output voltage waveform shown in Figure 7a is a 12-pulse rectifier output with a smaller amplitude ripple than the total DC output on the load when the outputs of the rectifier units are connected in series. The voltage exhibits a relatively stable characteristic with minimal ripple, which is an important requirement for EV charging systems. The lower ripple level reduces the need for extensive filtering and increases the overall efficiency of the DC-DC converter stage, leading to improved charging performance and battery life.

The grid current waveform presented in Figure 7b reveals that the current drawn by the 12-pulse rectifier is more sinusoidal than its six-pulse counterpart. The characteristic 12-pulse behavior results in a reduction in harmonic content, resulting in improved power quality. In the study comparing the 12-pulse Diode Rectifier Topologies (Abdel-Rahim et al., 2024), it is seen that the topology with the lowest THD value is the model proposed in this study. These characteristics make the 12-pulse rectifier a more suitable choice for high-power fast charging stations where grid compatibility and power quality are critical factors.

The harmonic spectrum shown in Figure 7c confirms that the 5<sup>th</sup> and 7<sup>th</sup> harmonics, which are particularly dominant in the six-pulse rectification, are significantly reduced. The elimination of these harmonics leads to lower THD in the grid, resulting in lower voltage distortion and reactive power demand in the grid.

In summary, the 12-pulse rectifier offers a compelling solution for high-power EV charging infrastructure due to lower DC voltage ripple, reduced harmonic distortion, and improved power quality. These features position the 12-pulse topology as a superior alternative to traditional six-pulse rectifiers in next-generation fast charging stations, providing higher efficiency and greater compliance with power quality standards.





**Figure 7.** Three-phase 12-pulse rectifier, a) DC output voltage waveform, b) current waveform drawn from the grid, c) grid current harmonic spectrum

#### 4. Conclusion

In this study, the harmonic effects of single-phase, three-phase six-pulse, and three-phase 12-pulse rectifier circuits used in EV charging applications are investigated. The results show that three-phase rectification significantly reduces the THD in the grid current compared to single-phase rectifiers. In particular, the six-pulse rectifier keeps the THD below 20% by eliminating the  $3^{rd}$  and  $3^{rd}$  harmonic components, while the  $30^\circ$  phase shift in the  $\Delta$ -Y connection used in the 12-pulse rectifier further improves the power quality by suppressing lower order harmonics such as the  $5^{th}$  and  $7^{th}$ . In addition, the 12-pulse rectifier provides a more stable DC link voltage with minimum ripple, which is crucial for efficient DC fast charging. As a result, it is seen that high-pulse rectifier topologies are more suitable for high-power EV charging stations as they provide improved power quality, reduced grid distortion, and higher efficiency without the need for an extra filter circuit at the output.

As future studies, the effects of 18-pulse or 24-pulse multi-pulse rectifier circuits on power quality and performance in EV charging stations can be investigated.

## Statement of Conflict of Interest

The author of the article declares that there is no conflict of interest.

## Author's Contributions

The author declares that she has contributed 100% to the article.

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