

Utility losses due to electric vehicle charging

1st Milan Stojanović
Faculty of Electronic Engineering
University of Niš
Niš, Serbia
milancestojanovic@elfak.rs

2nd Dejan Stevanović
Faculty of Electronic Engineering
University of Niš
Niš, Serbia
dejan.stevanovic@elfak.ni.ac.rs,
<https://orcid.org/0000-0002-4444-5496>

3rd Marko Dimitrijević
Faculty of Electronic Engineering
University of Niš
Niš, Serbia
marko.dimitrijevic@elfak.ni.ac.rs,
<https://orcid.org/0000-0001-9032-9595>

4th Dragan Vučković
Faculty of Electronic Engineering
University of Niš
Niš, Serbia
dragan.vuckovic@elfak.ni.ac.rs,
<https://orcid.org/0000-0001-9404-3818>

Abstract—The increasing presence of nonlinear loads in modern power systems has significantly changed energy consumption patterns. As these loads increase, active power becomes less dominant in the overall power delivery, leading to a greater dominance of reactive and distortion power components. Since utility mainly measures active power/energy, unaccounted losses result in grid inefficiency. This paper will focus on the losses introduced by electric vehicle chargers due to their nonlinear characteristics. The impact of reactive and distortion power on overall energy losses will be highlighted, emphasizing the need for improved measurement techniques and loss reduction strategies to enhance power system efficiency.

Keywords—Electric vehicle charging, Utility losses, Non-linear loads, Power measuring.

I. INTRODUCTION

The first ideas about electric vehicles (EVs) appeared in the 1830s when the first motorized carriage was created [1], [2]. However, this model was not developed further because it used a galvanic battery that couldn't be recharged.

Rechargeable batteries were introduced in the late 1850s [3], allowing the development of electric carriages. In the late 1880s, Scottish chemist William Morrison patented the first electric carriage with rechargeable batteries, which had a top speed of about 32 km/h and needed to be recharged after 80 km. Interest in EVs grew further at the end of the 19th and the beginning of the 20th century. At that time, New York had 60 electric taxis, and a third of all vehicles in the U.S. were electric.

However, in the 1920s, gasoline-powered cars rapidly developed and became the main competitors [1]. Due to cheap fossil fuel, these cars were more affordable and accessible than electric ones. EVs fell behind because of their low speed and short range; by 1935, they had nearly disappeared. In the 1960s and 1970s, rising gas prices in the USA and environmental concerns led to renewed interest in EVs. Despite efforts to develop practical models, their limited range and performance kept them from competing with fuel-powered cars.

The rapid development of internal combustion engine vehicles during the 20th century led to a significant increase in harmful emissions, mainly CO₂, which significantly impacted the greenhouse effect and accelerated global warming. These adverse ecological effects raised concerns among the public, the

scientific community, and governments, leading to a growing search for more sustainable and environmentally friendly solutions. As a response to these challenges, the development of EVs was revived in the 1990s [1]. The idea was to power these vehicles using electricity generated from alternative energy sources, such as solar power, wind power, and hydroelectric energy, which allow electricity generation with minimal or no harmful emissions and contribute to environmental sustainability.

In the last five years, the development of EVs has accelerated dramatically [4], driven by substantial investments, improved charging infrastructure, and growing environmental awareness among consumers. Moreover, advancements in energy storage technologies, mainly through lithium-ion batteries, improved the performance of EVs, making them a key factor in global efforts to reduce emissions, preserve the environment, and reduce dependence on fossil fuels. Today, EVs provide an alternative to conventional internal combustion engine cars and play a crucial role in global strategies for sustainable mobility by reducing emissions and improving energy efficiency. Figure 1 shows the number of EVs by year. It is estimated that by the end of 2025, it will exceed 77 million.

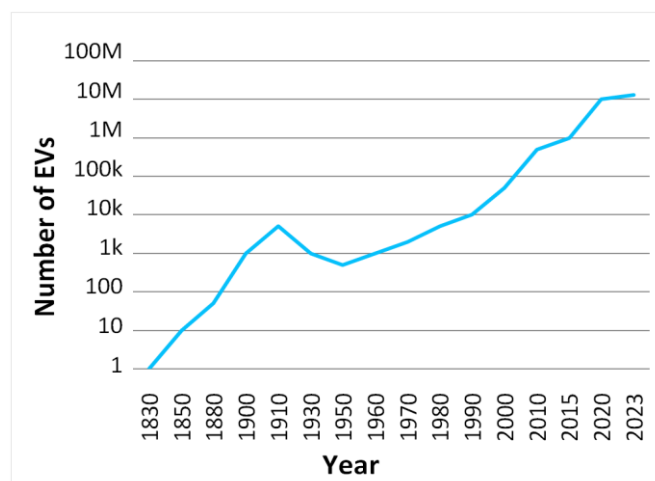


Fig. 1. Number of EVs by year.

EV chargers are non-linear loads because they use electronics, such as rectifiers, to convert alternating current

This work has been supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia [Grant Number: 451-03-136/2025-03/200102].

(AC) from the power grid into direct current (DC) required for charging batteries. This conversion process is essential since batteries can only store energy by DC charging. Unlike linear loads (e.g., incandescent bulbs), where the current is proportional to the voltage and the current waveform closely follows the voltage waveform, non-linear loads have distorted current and, hence, have a low power factor. In non-linear loads, the current waveform does not resemble the voltage waveform. Instead, their current contains higher harmonics in the spectrum, which disrupt the overall power quality, consequently producing many unwanted effects on the utility side, such as overloads on generators, transformers, cables, and relays [5], and causing voltage instability. Moreover, these types of loads increase losses in the utility [6], [7], [8].

Given the constant growth in EVs and their nature as nonlinear loads, assessing their impact on the power grid is necessary. This paper examines the losses caused by electric vehicle chargers stemming from their nonlinear behavior. It will underscore the effects of reactive and distortion power on total energy losses, highlighting the necessity for enhanced measurement methods and loss mitigation strategies to improve the power grid's efficiency. Additionally, the results of practical measurements will be analyzed, leading to conclusions on the extent to which EV chargers contribute to network losses.

The paper is organized as follows: Section 2 explores energy efficiency for different types of EV chargers. Section 3 discusses the components of apparent power and the methods for calculating them. Section 4 presents a comprehensive summary of the measurement results. Section 5 concludes this study.

II. ENERGY EFFICIENCY OF EV CHARGERS

Due to the growing number of nonlinear loads in the power grid and their negative impact on the system, international organizations have decided to develop standards regulating maximum allowable levels of harmonic distortion. Established standards such as IEC 61000 [9] and IEEE 519-1992 [10] define acceptable harmonic thresholds to ensure power quality. However, these standards do not prescribe specific corrective actions when limits are exceeded. Possible measures include disconnecting non-compliant consumers from the network or imposing fines.

The IEC 61000-3-2 standard is a global reference for electromagnetic compatibility (EMC), explicitly addressing harmonic emissions from electrical equipment. It limits the harmonic currents that devices with a rated input current of $\leq 16A$ per phase can introduce into the low-voltage grid, covering a wide range of residential, commercial, and industrial equipment.

The efficiency of chargers can vary depending on their type [11]. There are three main levels of EV chargers [12], [13].

Level 1 chargers use standard 230 V household outlets and are usually less efficient, with higher energy losses during charging. They are suitable for overnight charging or vehicles with smaller battery packs like plug-in hybrids. The main advantage of Level 1 chargers is their convenience and cost-effectiveness for home use, but their slow charging speed makes them less ideal for daily use with larger battery packs.

These chargers can introduce harmonic distortions into the grid, but the impact is generally lower than higher-level chargers due to their lower power output.

Level 2 chargers are generally more efficient than Level 1 chargers, with lower energy losses. They add about 15-95 km of range per hour of charging. Level 2 chargers are commonly found in homes, workplaces, and public charging stations. They offer a good balance of speed and convenience for daily use but require the installation of a dedicated 230/400 V outlet. These chargers can introduce more harmonic distortions into the grid than Level 1 chargers. The higher power levels and faster charging times can increase total harmonic distortion in the distribution network.

DC Fast Chargers, or Level 3 chargers, are the most efficient, adding about 90-150 km of range in 20 minutes. Level 3 chargers are ideal for commercial installations, highway rest stops, and urban charging hubs. They offer extremely fast charging, reducing range anxiety for long trips. However, they come with high installation and equipment costs and require specialized infrastructure. These chargers can introduce significant harmonic distortions into the grid due to their high power and rapid charging capabilities. The impact on power quality can be considerable, requiring mitigation measures such as active power filters and other power quality improvement devices.

III. COMPONENTS OF APPARENT POWER

One of the main negative effects of nonlinear consumers is the losses that occur in the utility. Italy's leading power distributor was one of the first to recognize the connection between significant losses and nonlinear loads on power lines [9]. Conventional electromechanical power meters are accurate and precise when measuring active power. Due to the increase in nonlinear loads, active energy no longer represents most of the total energy transferred to customers, leading to significant losses for energy distributors. To address this issue, it has been proposed that billing policies be changed to include reactive power measurement. The installation of these new meters began in 2001, and as of now, 99% have been replaced in Italy. The distributor decided to replace over 20 million household energy meters with upgraded electronic power meters capable of measuring active and reactive energy.

Measuring reactive power is crucial for understanding its impact on the energy system. Accurate measurement helps identify loss areas and implement techniques like power factor correction and efficient equipment to reduce them. Monitoring reactive power optimizes energy distribution, lowers costs, and enhances grid stability, leading to better energy management and lower consumer bills.

Apparent power represents the total power in an AC circuit, including both active and reactive power. It is denoted by the symbol S , measured in volt-amperes (VA), and is calculated as :

$$S = V_{RMS} \cdot I_{RMS} , \quad (1)$$

For linear loads (e.g., incandescent bulbs, resistive heaters), the current waveform is directly proportional to the voltage waveform. Apparent power in linear loads is calculated as:

$$S^2 = P^2 + Q_B^2, \quad (2)$$

where S represents apparent power, P represents active power, and Q represents reactive power, expressed in VA, W, and var units, respectively.

Active power is calculated as the product of RMS value of voltage and current of the same harmonic:

$$P = \sum_{h=1}^M V_{RMS_h} I_{RMS_h} \cos(\theta_h) = P_1 + P_H, \quad (3)$$

where h represents h^{th} harmonic, M the highest harmonic, θ the phase angle between current and voltage. P_1 is the fundamental active power component and denotes the power of the fundamental component ($h = 1$), while P_H represents the power of the higher harmonics ($h = 2, \dots, M$). Usually, the value of P_H is less than 3% of the total active power [14].

The calculation of reactive power is more complicated. The most recognized equation used in measurement equipment is known as Budeanu reactive power [7, 8], which is calculated as:

$$Q_B = \sum_{h=1}^M V_{RMS_h} I_{RMS_h} \sin(\theta_h) = Q_1 + Q_H, \quad (4)$$

where Q_1 is the reactive power and Q_H is the reactive power of all higher harmonics. The other versions of equations for reactive power calculation and their comparison for actual loads can be found in [9].

Nonlinear load characteristics lead to the appearance of harmonics that create distortions. In such cases, the square of the apparent power is higher than the sum of the squares of the active and reactive power, unlike with linear loads, as shown below:

$$S^2 > P^2 + Q_B^2, \quad (5)$$

In 1927, Budeanu recognized this and adjusted the equation for apparent power by introducing the concept of distortion power. The equation for calculating apparent power took the following form:

$$S^2 = P^2 + Q_B^2 + D^2, \quad (6)$$

where D represents the distortion power. It can easily be concluded that when there are no harmonics, meaning there is no distortion power ($D = 0$), the apparent power is calculated as shown in (1). The distortion power can be calculated when the values for S , P , and Q are known, as:

$$D^2 = \sqrt{S^2 - P^2 - Q_B^2}, \quad (7)$$

IV. MEASUREMENT OF APPARENT POWER COMPONENTS AND RESULT OVERVIEW

Figure 2 presents the block diagram of the measurement system, incorporating a Schrack Technik i-CHARGE CION Home 11 kW three-phase EV charger. Measuring equipment is

specifically designed to measure parameters based on the previously provided equations.

The measurements are conducted using an acquisition system that includes the measurement subsystem and a virtual instrument for data analysis and presentation. This subsystem features a connection circuit with CSNC241-500 Hall effect sensors, acquisition modules, and a data interface. The current sensor outputs are connected to the National Instruments NI9215 module, which features four channels that can capture voltage simultaneously at a 16-bit resolution, with a sample rate of 100kS/s. Voltages are measured directly through the National Instruments NI9227 acquisition module. This module offers four channels for simultaneous current sampling, with a resolution of 24 bits, a sampling rate of 50k samples per second, and a channel-to-channel isolation of 250V RMS.

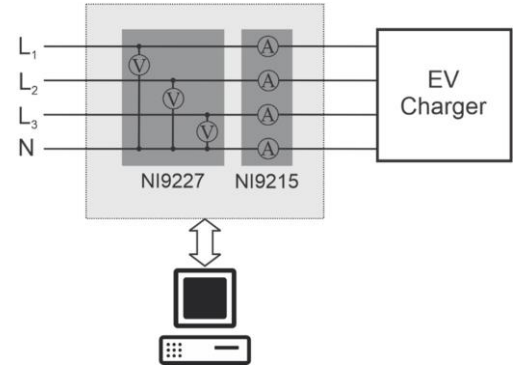


Fig. 2. The measurement system consists of acquisition modules, current sensors, and a PC running a virtual instrument.

Using the specified measuring equipment, we obtained the power grid parameters during the 5-hour charging period. Table 1 shows average values of these parameters before, during, and after the charging process for phase L1, as well as maximum and minimum values. Before and after charging, with current near 0A, both active and reactive power are nearly zero, while distortion power remains slightly above zero. The current is around 15A during charging, and active power is about 3.6kW per phase. Significant changes in reactive and distortion power occur during charging, which will be detailed with graphs later.

TABLE I. POWER GRID PARAMETER VALUES DURING CHARGING FOR PHASE L1

	V_{RMS} [V]	I_{RMS} [A]	P [W]	Q_B [var]	D [var]
Before charging	238.824	0.0251	0.0698	0.1992	5.8245
During charging	237.076	15.506	3672.09	-224.48	98.541
After charging	240.518	0.0514	0.0732	0.2107	11.938
Min. value	236.175	0.0234	-0.0980	-342.25	5.0241
Max. value	241.096	15.623	3697.85	0.3547	118.65

Figure 3 presents a graph illustrating the change in active power value during charging process.

According to estimates, the number of electric vehicles (EVs) will exceed 77 million by 2025 [4]. This increase will result in more EV chargers and greater electricity consumption. The graph in Figure 3 shows that the active power is around zero at the beginning, before the start of charging, and at the end, after charging is completed. According to estimates, in 2025, electric vehicles will be able to travel 500–1000km on a single charge [15]. Assuming an average charger power of 10.8kW and a single 5-hour charging session per week, the total energy consumption of an EV charger is estimated to be 54kWh per week. For 77 million chargers, this corresponds to a total weekly energy consumption of $E_{total} = 1.25TWh$. The monthly consumption would be approximately 16.63TWh, and the annual consumption would be around 199.5 TWh.

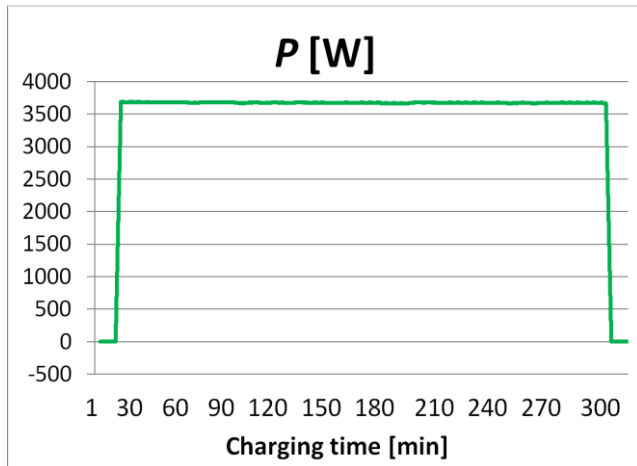


Fig. 3. Active power value over time.

The main emphasis was on monitoring the reactive power (Q_B) value. Figure 4 shows the change in the reactive power value over time during the previously mentioned charging period.

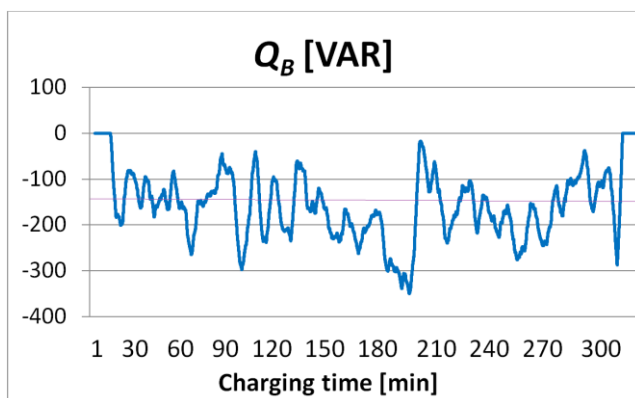


Fig. 4. Reactive power value over time.

Figure 4 shows that the reactive power is also near zero before and after charging. During the charging process, there are noticeable fluctuations in the values, mostly negative. The value for Q_B reaches up to -300var, with a slight exception of one spike of around -340var. While this value alone is not enough to have a significant impact, it becomes significant when considering the number of EVs and the charging time.

The average value of Q_B is approximately -154 var per phase, with consumption equating to about 4.3% of the consumption for P , which amounts to around 8.58TWh annually. When considering the monetary value, with 1 kWh in Europe costing about 10 cents [16], the losses due to reactive power amount to approximately 932.7 million euros. This is a very significant figure.

Figure 5 illustrates the change in distortion power values during the charging process. As shown, the distortion power is lower than the reactive power; however, its impact on overall consumption should not be overlooked.

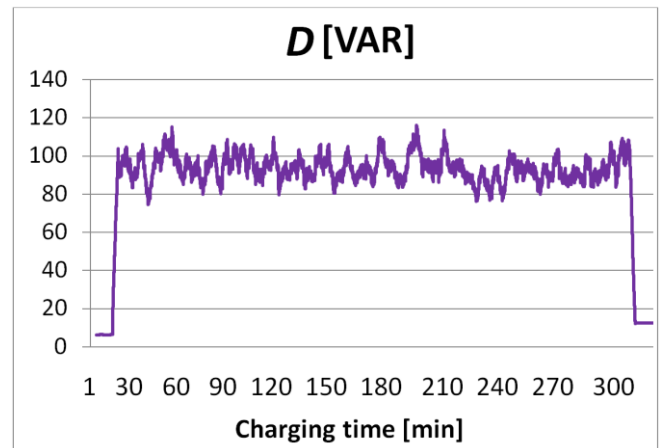


Fig. 5. Distortion power value over time.

V. CONCLUSION

Given inadequate measuring policies, utility systems are experiencing increasing losses due to the growing presence of non-linear consumers, including electric vehicle chargers. As the number of electric vehicles and their chargers continues to rise, these losses will escalate over time, leading to additional costs for utilities and necessitating further investments in infrastructure to mitigate these losses. Detecting and accurately measuring reactive power/energy and distortion power/energy is essential for optimizing efficiency and minimizing unnecessary losses on the grid.

REFERENCES

- [1] The History of the Electric Car | Department of Energy.
- [2] A brief history of the electric car - Energy Saving Trust.
- [3] P. Kurzweil, Gaston Planté and his invention of the lead–acid battery- The genesis of the first practical rechargeable battery, *Journal of Power Sources*, Volume 195, Issue 14, 2010, Pages 4424-4434, ISSN 0378-7753, <https://doi.org/10.1016/j.jpowsour.2009.12.126>.
- [4] Global EV Outlook 2024, <https://www.iea.org/reports/global-ev-outlook-2024?form=MG0AV3>.
- [5] “Control of harmonics in electrical Power System,” American Bureau of Shipping, May 2006.
- [6] Stevanović, D., Petković, P.: *The Losses at Power Grid Caused by Small Nonlinear Loads*, Serbian Journal of Electrical Engineering, Volume 10, No. 1, February 2013, Čačak, Serbia, 2013, pp. 209-217, ISSN 1451-4869.
- [7] Dejan Stevanović, Predrag Petković: *Utility needs smarter power meters in order to reduce economic losses*, Facta Universitatis Series: Electronics and Energetics Vol. 28, No 3, September 2015, 2015, pp. 407-421, doi:10.2298/FUEE1503407S.
- [8] Stevanović, D., Andrejević Stošović, M., Dimitrijević, M., Petković, P. (2018). Utility losses due to cryptocurrency mining. Web proceedings of

the *10th International Conference ICT Innovations*, Ohrid, ISSN 1857-7288.

- [9] M. N. Z. Abidin, IEC 61000-3-2 Harmonics Standards Overview, Schaffner EMC Inc., Edison, NJ, USA.
- [10] Thomas M. Blooming, Daniel J. Carnovale, Application of IEEE STD 519-1992 Harmonic Limits.
- [11] Brenna, M., Foadelli, F., Leone, C. *et al.* Electric Vehicles Charging Technology Review and Optimal Size Estimation. *J. Electr. Eng. Technol.* 15, 2539–2552 (2020). <https://doi.org/10.1007/s42835-020-00547-x>.
- [12] Bernal-Vargas, J. B., Castro-Galeano, J. C., Tibaduiza-Rincón, E. E., López-Lezama, J. M., & Muñoz-Galeano, N. (2023). Prospective Analysis of Massive Integration of Electric Vehicle Chargers and Their Impact on Power Quality in Distribution Networks. *World Electric Vehicle Journal*, 14(12), 324. <https://doi.org/10.3390/wevj14120324>.
- [13] Srivastava, A., Manas, M. & Dubey, R.K. Electric vehicle integration's impacts on power quality in distribution network and associated mitigation measures: a review. *J. Eng. Appl. Sci.* 70, 32 (2023). <https://doi.org/10.1186/s44147-023-00193-w>.
- [14] J. G. Webster, The measurement, instrumentation, and sensors handbook, IEEE Press, 1999, Chapter 40.
- [15] Electric car battery range: <https://cultura.org/electric-car-battery-range/>.
- [16] Map of electricity spot price in Europe, <https://www.energyprices.eu/?form=MG0AV3&form=MG0AV3>.