Investigating power quality issues in electric buggy battery charger systems: analysis and mitigation strategies

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ABSTRACT

This paper investigates power quality issues in the battery charger system of an electric buggy. Key power quality parameters such as total harmonic distortion (THD), power factor (PF), input voltage, and input current, were measured and analyzed during the charging process. The findings reveal significant power quality challenges, with THD levels exceeding IEEE 519 standards, indicating inefficiencies and potential risks such as increased heating and stress on charger components. Power factor readings reveal a substantial reactive power component, further contributing to inefficiency. To address these issues, the study recommends implementing harmonic mitigation techniques, such as passive and active filters, to reduce THD levels, using power factor correction methods, and optimizing charging algorithms to manage power demand more effectively. Continuous monitoring of charging parameters is essential for maintaining optimal performance and reliability. Adhering to standards is crucial for the efficient and reliable operation of electric vehicle (EV) charging systems, with regular compliance testing and benchmarking necessary to identify improvement areas and maintain a high-quality charging infrastructure. The proposed solutions aim to develop a sustainable and efficient charging system for electric buggies, providing valuable insights and recommendations for future research and development in power electronics and drive systems for EV applications.

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1. INTRODUCTION

Power quality is a critical factor in the design and operation of electric vehicle (EV) charging systems [1]–[3]. Poor power quality can lead to inefficiencies, increased operational costs, and potential damage to the electrical infrastructure. Key power quality parameters include total harmonic distortion (THD), power factor (PF), voltage stability, and current stability. These parameters directly impact the performance and longevity of EV charging systems [4]–[13], [14], [15].

THD is a measure of the distortion of the voltage or current waveform caused by harmonics. High levels of THD indicate the presence of significant harmonic frequencies, which can lead to increased losses in electrical systems and potential interference with other devices [16]. Several studies have highlighted the impact of THD on EV chargers. For instance, Lenka and Panda [17] demonstrated that high THD levels in EV chargers could lead to reduced efficiency and increased heating of components. IEEE 519 provides guidelines for acceptable THD levels, emphasizing the importance of maintaining low harmonic content to ensure system reliability and efficiency.

The PF is a measure of how effectively the electrical power is being used. A low PF indicates that a large portion of the power is reactive, leading to inefficiencies in the power delivery system. Reactive power does not perform any useful work but contributes to the overall power consumption, increasing the burden on the power supply. Researchers such as Goval *et al.* [18] have explored various power factor correction (PFC) techniques for EV chargers, including the use of passive and active filters, to improve the power factor and reduce reactive power.

Voltage stability is crucial for the reliable operation of EV chargers. Fluctuations in input voltage can lead to inefficient charging and potential damage to the battery and charger components. Studies by Kim *et al.* [19] have shown that stable voltage supply is essential for maintaining the performance and lifespan of EV chargers. Techniques such as voltage regulation and real-time monitoring have been proposed to ensure voltage stability during the charging process.

Similar to voltage stability, maintaining a stable current is vital for efficient EV charging. Fluctuations in current can cause uneven charging, leading to reduced battery life and potential safety hazards. Research by Suroso [20] has emphasized the importance of current regulation in EV chargers, suggesting the use of advanced control algorithms to manage current stability.

To address the issues of high THD and low power factor, various harmonic mitigation techniques have been proposed. Passive filters, such as inductors and capacitors, can effectively filter out specific harmonic frequencies. Active power filters dynamically compensate for harmonics by injecting counteracting currents. Hybrid filters combine the benefits of both passive and active filters, offering a comprehensive solution for harmonic mitigation. Studies by Fujita *et al.* [21] have demonstrated the effectiveness of these techniques in improving power quality in EV charging systems.

Optimized charging algorithms play a crucial role in managing power demand and improving power quality. These algorithms adjust the charging parameters based on real-time data to ensure efficient energy usage and minimize harmonic distortion. Research by Ibrahim *et al.* [22] has shown that advanced charging algorithms can significantly enhance the performance of EV chargers by optimizing the charging process and reducing power quality issues.

Continuous monitoring of power quality parameters and adaptive control systems are essential for maintaining optimal performance in EV chargers. Real-time monitoring allows for the early detection of power quality issues, enabling prompt corrective actions. Adaptive control systems adjust the charging parameters dynamically based on the monitored data, ensuring efficient and reliable operation. Studies by Monadi *et al.* [23] have highlighted the benefits of integrating real-time monitoring and adaptive control in EV charging systems.

IEEE 519 standards provide guidelines for maintaining acceptable levels of harmonic distortion and ensuring power quality [24]. Compliance with these standards is crucial for the efficient and reliable operation of EV chargers. Research by Chaudhary *et al.* [25] has emphasized the importance of adhering to IEEE 519 standards, suggesting that regular testing and benchmarking are necessary to ensure compliance and identify areas for improvement.

The literature review highlights the critical importance of power quality in EV charging systems and the various techniques proposed to address power quality issues. THD, PF, voltage stability, and current stability are key parameters that impact the efficiency and reliability of EV chargers. Harmonic mitigation techniques, optimized charging algorithms, real-time monitoring, and adaptive control systems are essential for improving power quality. Compliance with IEEE 519 standards is necessary to ensure the efficient and reliable operation of EV chargers. This review provides a comprehensive overview of the current state of research in power quality for EV charging systems, identifying key challenges and potential solutions.

2. METHOD

The study utilizes a comprehensive experimental setup to investigate power quality issues in the battery charger system of an electric buggy, specifically the GoBugs (Model: GT-N4) equipped with a lithium iron phosphate ($LiFePO_4$) battery as shown in Figure 1. The battery has a capacity of 100 Ah (5120 Wh) and operates at a voltage of 51.2 V. The charging system setup, as illustrated in Figure 2, encompasses the essential components for detailed power quality analysis.

To measure and capture the power quality parameters during the charging operation, a FLUKE 1777 power quality analyzer as shown in Figure 3 is employed. This high-precision instrument is capable of measuring a wide range of power quality parameters, including THD, PF, voltage, and current. Additionally, the YOKOGAWA WT333E digital power meter is used to verify the measurements obtained from the FLUKE 1777, ensuring accuracy and reliability of the results.

The charging profile of the E-Buggy's battery is meticulously monitored, starting from a voltage of 41 V (0% state of charge) to 54 V (100% state of charge). The total charging duration is 410 minutes (6 hours and 54 minutes). During this period, various power quality parameters are recorded at different intervals to analyze the charging process comprehensively.

The FLUKE 1777 power quality analyzer captures waveforms and detailed measurements of the supply current, input voltage, power factor, and THD throughout the charging process. The data collection is done at regular intervals, ensuring a thorough analysis of the power quality issues at each stage of the charging cycle. THD levels are measured to determine the extent of harmonic distortion present in the supply current and voltage. High THD levels indicate significant harmonic content, which can lead to inefficiencies and potential damage to the charger components. The power factor is monitored to assess the efficiency of power usage. A low power factor suggests a high reactive power component, leading to increased losses in the electrical system. Power factor correction techniques are evaluated based on these measurements.

Input voltage and current are recorded to analyze their stability throughout the charging process. Stable voltage and current are crucial for efficient and reliable charging operation. The power consumption is tracked to understand the overall energy usage during the charging cycle. This helps in identifying any inefficiencies and potential areas for optimization.

The waveform data obtained from the FLUKE 1777 power quality analyzer is cross-verified with the measurements from the YOKOGAWA WT333E digital power meter. This step ensures the accuracy and reliability of the data collected, providing a robust basis for the analysis. The collected data is processed and analyzed to identify power quality issues and their impact on the charging system's efficiency. Statistical analysis is performed to understand the variations and trends in the power quality parameters. The results are compared with the standards set by IEEE 519 to assess compliance and identify areas for improvement.

The methodology outlined in this study presents a comprehensive framework for examining power quality issues specifically related to the battery charger system of an electric buggy. This approach involves the use of advanced measurement tools to collect precise electrical parameters, enabling a thorough analysis of factors that may contribute to inefficiencies such as voltage fluctuations, harmonic distortions, and power losses. By systematically evaluating these issues, the research aims to identify key problem areas and develop targeted mitigation strategies to optimize the performance, efficiency, and long-term reliability of the EV charging system. Additionally, the findings from this study could serve as a valuable reference for improving similar battery charging infrastructures in other electric vehicles.

Figure 1. E-Buggy model GT-NT with the LiFePO4 type battery

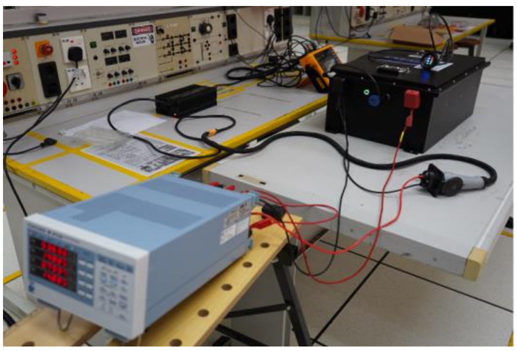

Figure 2. Setup for operation of battery charger system for electric buggy

Figure 3. FLUKE 1777 power quality analyzer

3. RESULTS AND DISCUSSION

The analysis of THD of the supply current for the electric buggy during its charging operation, as shown in Figure 4, reveals significant power quality issues. The recorded THD value is alarmingly high at 143.1%, indicating a severe deviation from acceptable standards. According to the IEEE 519 Standard, permissible THD levels are 5% for individual harmonics and 8% for total harmonic distortion in systems with voltages below 69 kV. The observed values far exceed these limits, pointing to substantial inefficiencies and potential damage to electrical components. To address these issues, it is recommended to implement harmonic mitigation techniques such as passive and active power filters, or a combination of both. Additionally, improvements in charger design, including phase-shifted control and advanced switching techniques, can help reduce harmonic generation. Continuous power quality monitoring and regular compliance testing per IEEE 519 standards are essential to ensure that the system remains within acceptable limits and to promptly address any deviations. This study underscores the critical need for adherence to power quality standards in EV charging systems to promote sustainable and reliable electric vehicle infrastructure.

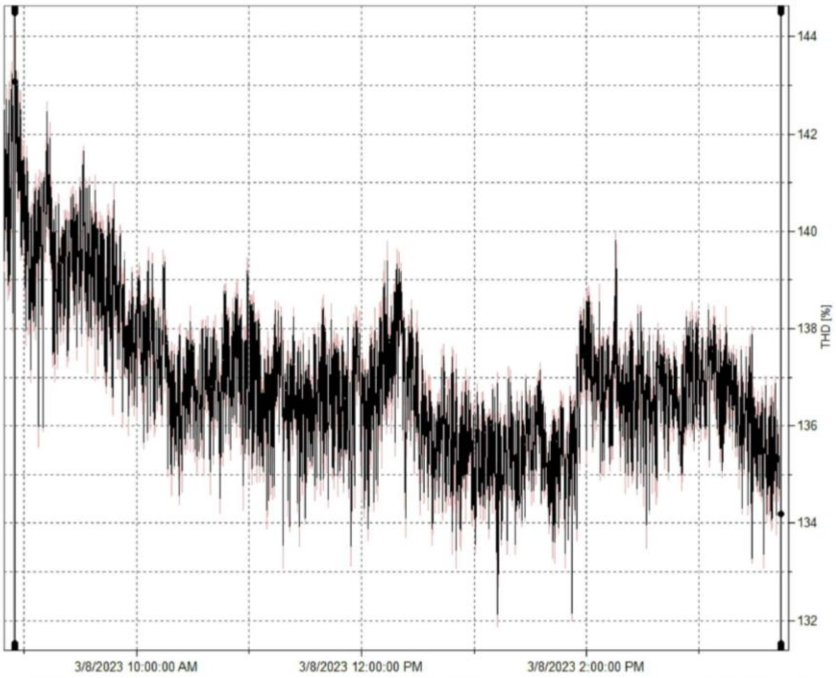

Figure 4. THD of supply current waveform captured using FLUKE 1777 power quality analyzer (x-axis: time in hour, y-axis: THD level in %)

Figure 5 shows the PF graph of the electric buggy during its charging operation. The graph reveals significant fluctuations and generally low values, indicating potential power quality issues. The average power factor decreased from 0.562 (capacitive) at 8:49:35 AM to 0.321 (capacitive) at 3:44:13 PM, with a maximum value of 0.589 and a minimum of 0.265 over approximately 6 hours and 54 minutes. These low PF values suggest that a substantial portion of the power supplied is not being effectively converted into useful work, pointing to inefficiencies in the battery charger system. A low PF implies a higher reactive power component, leading to increased electrical system losses and reduced efficiency. High reactive power can stress the electrical infrastructure, causing overheating and reducing component lifespan. According to IEEE 519 standards, maintaining a high PF is essential for efficient energy use and minimizing power quality issues. To address these issues, implementing power factor correction techniques, such as using capacitors or synchronous condensers, can improve the PF by compensating for the reactive power component. Additionally, harmonic mitigation techniques, such as harmonic filters, can reduce THD levels, which can also help improve the PF. Optimizing charging algorithms to manage reactive power more effectively and continuously monitoring and adjusting charging parameters based on PF readings are crucial steps. Ensuring compliance with IEEE 519 standards through regular testing and benchmarking is vital for maintaining a high-quality and efficient charging infrastructure. This analysis emphasizes the importance of integrating power quality improvements with energy management strategies to achieve optimal performance in electric vehicle charging systems.

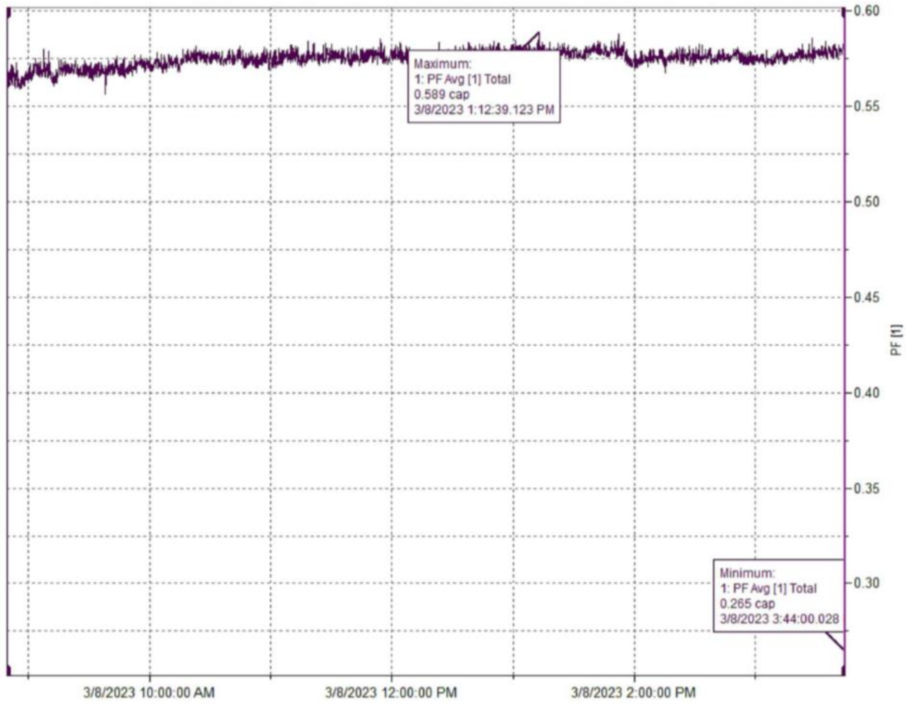

Figure 5. Power factor graph captured using FLUKE 1777 power quality analyzer
(x-axis: time in hour, y-axis: power factor)

The energy graph of the electric buggy during its charging operation as presented in Figure 6 shows a significant variation in power demand over time. Initially, the energy consumption is 5.509 Wh over a 10-minute interval at 8:50:00 AM, which rapidly increases and stabilizes at approximately 151.946 Wh over a 10-minute interval by 3:40:00 PM. This pattern indicates the typical behavior of an EV battery charger, where the initial charging phase draws less power, and the demand increases as the battery reaches higher states of charge. The substantial increase in energy consumption over the observed period highlights the need to assess power quality issues, specifically the THD, which was previously noted to be significantly above the IEEE 519 standard limits. High THD levels suggest inefficient energy usage, which can lead to excessive losses and potential damage to the charging infrastructure. Implementing harmonic mitigation techniques, such as passive and active filters, and optimizing charging algorithms are essential steps to enhance energy efficiency. Furthermore, continuous real-time monitoring and adaptive control systems can ensure better energy management and compliance with power quality standards. This analysis underscores the importance of integrating power quality improvements with energy consumption evaluations to develop a sustainable and efficient EV charging system.

Figure 7 shows the frequency graph of the electric buggy during its charging operation. The graph shows that the supply frequency remains stable, with readings of 49.97 Hz and 50.08 Hz, reflecting a minimal variation of 0.11 Hz over approximately six hours. This indicates a robust power source capable of maintaining consistent performance during charging. Although IEEE 519 standards focus on harmonic distortion, maintaining a stable frequency is crucial for the optimal operation of power electronics and control systems, ensuring efficient energy conversion and minimizing losses. Despite the stable frequency, previously noted high THD levels suggest significant power quality issues.

The input current graph of the electric buggy during its charging operation as shown in Figure 8 shows an increase in the average current from 6.10 to 6.95 A, reflecting a delta of 0.86 A over a period of approximately 6 hours and 54 minutes. This gradual increase in current suggests a higher demand as the battery charges, typical of EV battery chargers which often require more current in the latter stages of charging to reach full capacity. From a power quality perspective, the stability of the current over time is a positive indicator; however, high current levels can exacerbate harmonic distortion issues. Previously identified high THD levels in this system point to significant power quality problems. High THD not only leads to inefficiencies in energy usage but also potential overheating and damage to electrical components due to excessive harmonic currents.

The input voltage graph of the electric buggy during its charging operation as shown in Figure 9 shows a slight increase in the average voltage from 230.2 to 233.1 V, with a delta of 2.9 V over approximately more than 6 hours. This relatively small variation in input voltage indicates a stable supply voltage during the charging process, which is critical for the efficient operation of power electronics in the battery charger system. In the context of power quality, maintaining a stable input voltage is essential to ensure the reliable performance of the charger and to prevent issues such as voltage sags, swells, or transients, which can negatively impact the charging efficiency and lifespan of the battery.

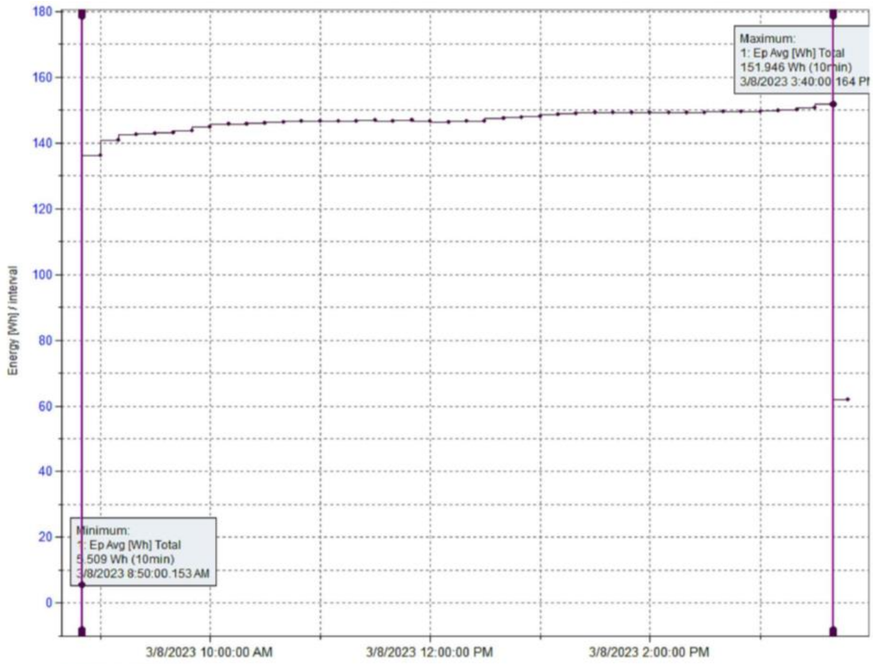

Figure 6. Energy graph waveform captured using FLUKE 1777 power quality analyzer (x-axis: time in hour, y-axis: energy in Wh)

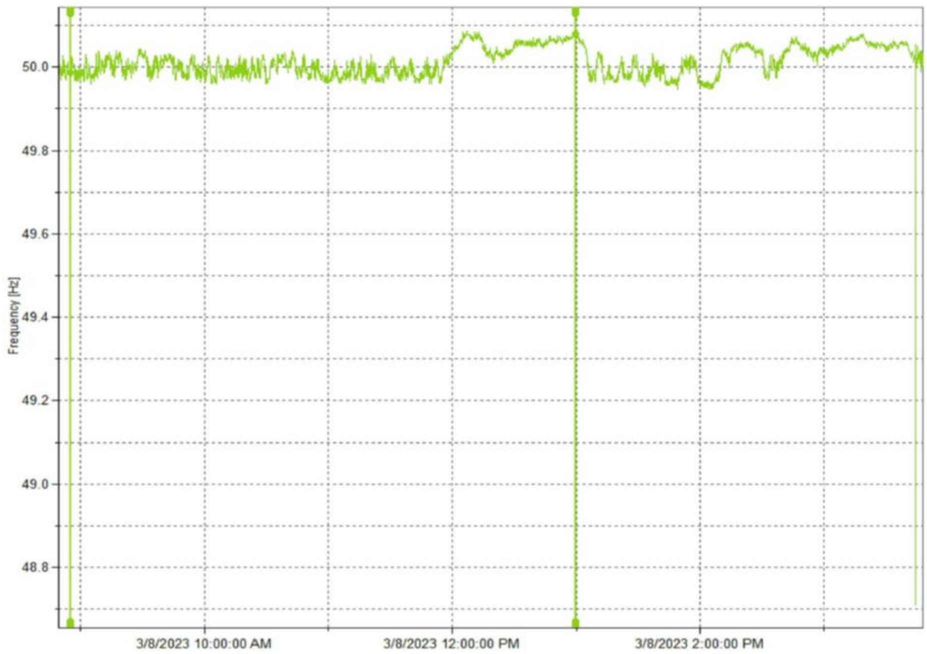

Figure 7. Frequency graph waveform captured using FLUKE 1777 power quality analyzer (x-axis: time in hour, y-axis: frequency in Hz)

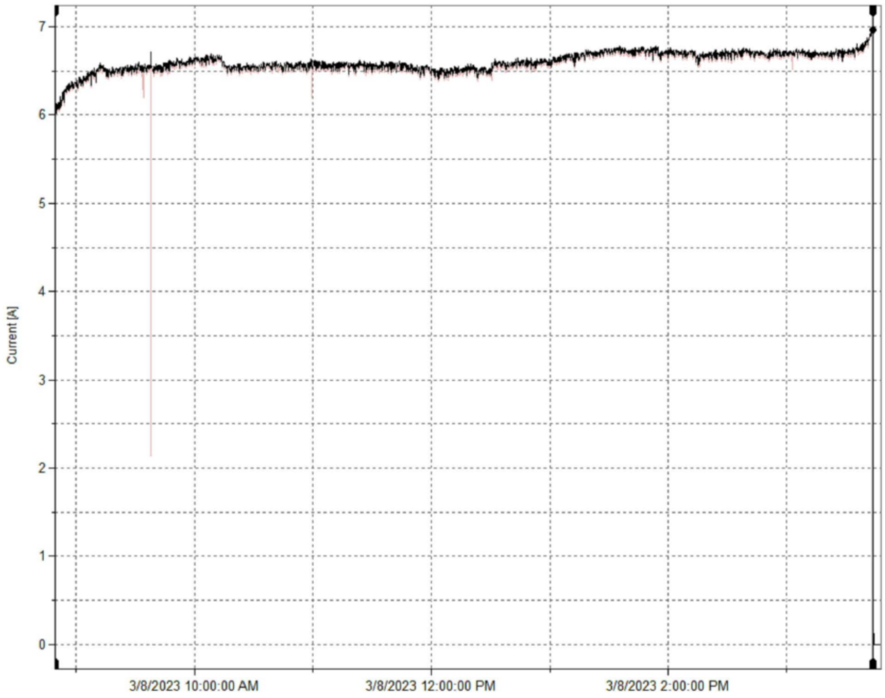

Figure 8. Input current graph waveform captured using FLUKE 1777 power quality analyzer (x-axis: time in hour, y-axis: input current)

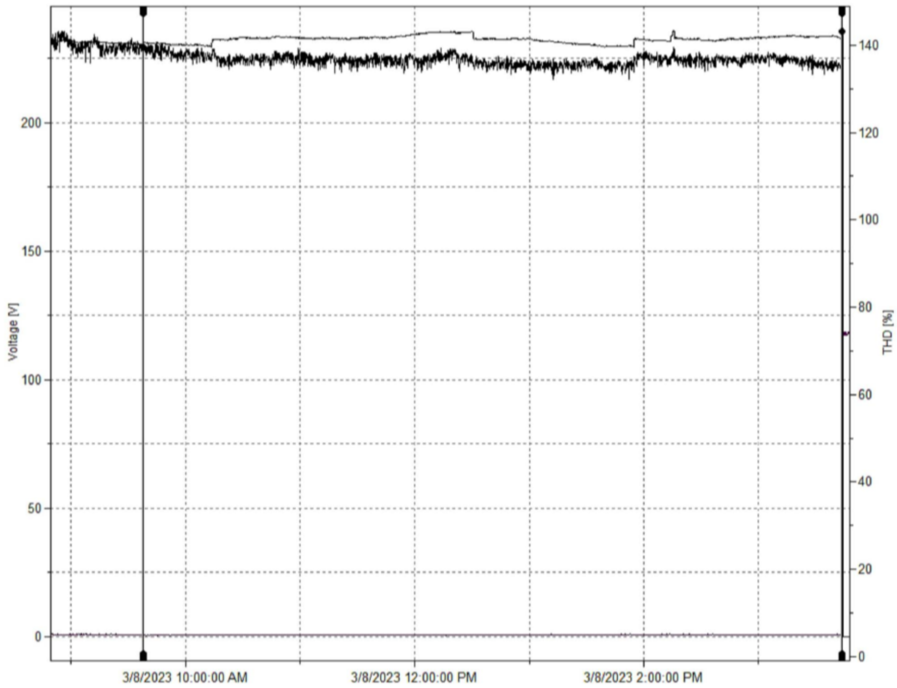

Figure 9. Input voltage graph waveform captured using FLUKE 1777 power quality analyzer (x-axis: time in hour, y-axis: input voltage)

The power graph of the electric buggy during its charging operation, as shown in Figure 10, indicates relatively stable power consumption, increasing from 809.0 to 960.0 W, with a delta of 151.0 W over approximately 6 hours and 54 minutes. This gradual rise in power reflects the typical behavior of an EV battery charger, where power demand increases as the battery approaches a higher state of charge. This stability in power consumption is a positive indicator of the charger's performance; however, power quality issues such as THD and PF need to be considered to ensure overall system efficiency. High THD levels, previously identified in the system, suggest that a significant portion of the power is not being effectively utilized due to harmonic losses. This can lead to increased heating and potential damage to the charger components, ultimately affecting the system's reliability and lifespan. According to IEEE 519 standards, maintaining low THD levels is crucial for minimizing power quality issues and ensuring efficient energy usage. Additionally, the PF of the system needs to be addressed. Low PF values, as previously observed, indicate that a substantial portion of the power is reactive rather than active, leading to inefficiencies in the power delivery system. To address these issues comprehensively, it is recommended to implement harmonic mitigation strategies such as passive and active filters, optimize the charging algorithm, and incorporate continuous real-time monitoring and adaptive control systems. These measures will help improve power quality, enhance system efficiency, and ensure the longevity and reliability of the electric buggy's battery charger system.

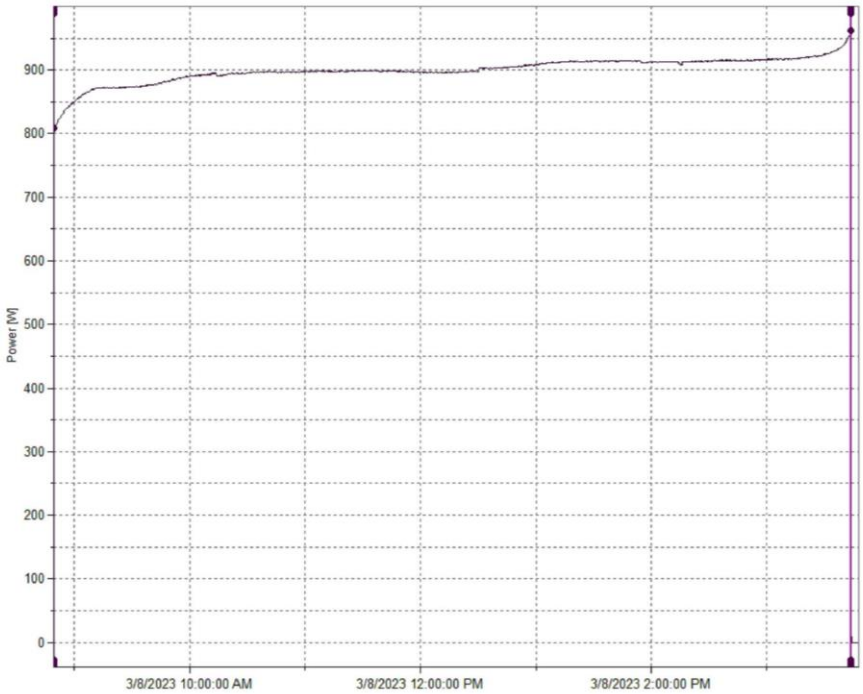

Figure 10. Power graph waveform captured using FLUKE 1777 power quality analyzer (x-axis: time in hour, y-axis: power)

4. CONCLUSION

This study investigates the power quality issues in the battery charger system of an electric buggy, focusing on the GoBugs (Model: GT-N4) with a LiFePO4 battery. Using the FLUKE 1777 power quality analyzer and the YOKOGAWA WT333E digital power meter, key power quality parameters, including THD, PF, input voltage, and input current, were measured and analyzed during the charging process. The results show significant power quality issues, with THD levels exceeding IEEE 519 standards, indicating inefficiencies and potential risks such as increased heating and stress on charger components. The power factor readings reveal a considerable reactive power component, further contributing to inefficiency. Although the voltage and current profiles are relatively stable, comprehensive power management is needed to ensure efficient energy use. To mitigate these issues, the study recommends several strategies: implementing harmonic mitigation techniques such as passive and active filters to reduce THD levels, using power factor correction methods like capacitors and synchronous condensers, and optimizing charging algorithms to manage power demand more effectively. Continuous monitoring and real-time adjustments of charging parameters are essential for maintaining optimal performance and reliability. Adhering to IEEE 519 standards is crucial for the efficient and reliable operation of EV charging systems. Regular compliance testing and benchmarking are necessary to identify improvement areas and maintain a high-quality charging infrastructure. By integrating power quality improvements with energy management strategies, a sustainable and efficient charging system for electric buggies can be developed. In summary, this paper provides a detailed analysis of power quality issues in an electric buggy battery charger system and offers practical solutions to enhance performance and reliability. The insights and recommendations are intended to guide future research and development in power electronics and drive systems for EV applications, contributing to the advancement of sustainable and efficient electric vehicle infrastructure.

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AUTHOR CONTRIBUTIONS STATEMENT

Wan Muhamad Hakimi Wan Bunyamin contributed to methodology, software, validation, investigation, data curation, writing - original draft and visualization. Samshul Munir Muhamad contributed to software, investigation, data curation and visualization. Wan Salha Saidon contributed to software and investigation. Rahimi Baharom contributed to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing (original draft and review & editing), visualization, supervision, project administration, and funding acquisition. All authors have read and approved the final manuscript.

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Samshul Munir Muhamad			✓			✓		✓			✓			
Wan Salha Saidon			✓			✓								
Rahimi Baharom	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

This research does not require ethical approval as it does not involve human participants, animal subjects, or sensitive data.

DATA AVAILABILITY

The data supporting this study's findings are available from the corresponding author, RB, upon reasonable request.

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