NOVEL ZETA CONVERTER FOR ELECTRICAL VEHICLE BATTERY WITH REDUCED SWITCHING LOSSES

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Abstract: A non-isolated Zeta converter topology with reduced switch voltage stress is proposed for power factor correction (PFC) in battery electric vehicle (BEV) chargers to improve power quality. Conventional boost PFC converters widely used for BEV charging suffer from drawbacks like lack of input-output isolation, high voltage stress across the switch, and limited voltage boost capability. The proposed Zeta PFC converter mitigates these issues through a modified input stage that clamps the voltage across the main switch at the input level, thereby reducing voltage stress. an isolated, regulated DC output suitable for BEV battery charging. Comprehensive MATLAB/Simulink models are developed using the Sim-Power-Systems library to analyze the proposed converter's performance under varying input/load conditions. Simulation results validate the efficacy of the topology in providing power factor correction while reducing semiconductor voltage stress. The proposed PFC converter offers an efficient, robust and cost-effective solution for enhanced power quality in single-phase BEV charging applications by combining the advantages of the Zeta topology with lower govindniranjan16switch voltage stress.

Keywords: Power Factor Correction, Reduced Switch Voltage Stress, Battery Electric Vehicle Charging, Zeta Converter.

1 Introduction

In modern electrical power systems, maintaining high power quality and an optimal power factor is crucial for efficient and reliable operation. However, the widespread use of electronic devices and non-linear loads, such as AC-DC rectifiers followed by bulk capacitors, has led to significant power quality degradation and harmonic distortion in the supply lines. These issues not only violate international harmonic regulations but also result in a poor power factor at the mains, leading to increased energy losses and reduced system efficiency.

The Importance of Power Factor

The power factor provides a measure of the efficiency of power utilization in the system and is directly related to the distortion of the line current waveform. A lower power factor implies higher current distortion and increased energy losses in the distribution system, leading to higher operational costs and reduced energy efficiency.

Power Factor Correction Techniques

[1] To address the power quality issues and improve the power factor, various power factor correction (PFC) techniques have been developed. These techniques aim to shape the input current waveform to follow the input voltage profile, effectively emulating a pure resistive load and minimizing harmonic distortion.

[2] The literature presents various PFP configurations, each offering distinct characteristics and trade-offs. These topologies include the Buck, Boost, Buck-Boost, Cuk, and SEPIC converters. Among these alternatives, the Boost converter has gained widespread adoption due to its relatively simple topology and straightforward control implementation.

However, despite its popularity, the Boost PFP topology suffers from several inherent drawbacks that can limit its performance and applicability in certain scenarios. [3] The ability to provide galvanic isolation, which is crucial for safety and noise immunity in many applications.

Additionally, the Boost PFP topology imposes restrictions on the output voltage, which cannot be lower than the peak input voltage. This constraint can pose challenges in applications requiring precise voltage regulation or a wide range of output voltages.

Furthermore, the Boost PFP exhibits a high starting current, which can stress the components and potentially lead to reliability issues, particularly in applications with frequent start-stop cycles or sensitive load requirements.

Lastly, the lack of inherent overload protection in the Boost PFP topology can expose the system to potential damage or failure in the event of excessive load conditions or short-circuit scenarios.

[5] While the Boost PFP has proven to be a valuable solution in many applications, these inherent limitations have prompted researchers and engineers to explore alternative PFP topologies that can address these shortcomings while maintaining the benefits of improved power factor and reduced harmonic distortion.

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[6] By continuously investigating and developing new PFP configurations, the power electronics industry aims to provide more robust, efficient, and versatile solutions tailored to the diverse requirements of modern electrical systems, ensuring optimal power quality and reliable operation across a wide range of applications.

Control Strategies for Power Factor Pre-regulators

The control strategy for power factor pre-regulators can be realized through two main approaches:

1.1 Power Quality Issues in Domestic Appliances

[7] Many domestic appliances incorporate mains rectification circuits, which are a significant contributor to harmonic distortion in the supply lines. When numerous such devices draw reactive power from the same supply system, it leads to a substantial amount of reactive current flow and harmonic generation, adversely affecting the power factor of the transmission line.

Improving the power factor not only enhances the degree of power utilization but also reduces energy waste in the power system. Consequently, addressing power factor issues and implementing appropriate power factor correction circuits have become a crucial aspect of maintaining power quality standards and ensuring efficient power distribution.

1.2 Rectifier Circuits and Harmonic Distortion

[8] Harmonic distortion in the line current can cause various problems, such as increased power losses, electromagnetic interference, overheating of transformers and motors, and premature aging of electrical equipment. Therefore, addressing harmonic distortion through effective power factor correction techniques is crucial for maintaining power quality and ensuring reliable operation of electrical systems.

1.3 Power Factor Correction Circuits

[9] To mitigate the issues caused by harmonic distortion and poor power factor, electronics engineers have focused on developing new concepts and approaches for power factor correction circuits. These circuits aim to meet international standards and ensure optimal performance of utility systems by reducing reactive power drawn from the supply and minimizing harmonic generation.

As consumer electronics continue to proliferate, the power quality deteriorates, and the reactive power drawn from the supply system increases due to the widespread use of rectification and bulk capacitors at the input stage. To address these challenges, various power factor correction and harmonic reduction methods have been developed, with some proving more effective than others in delivering good performance for utility systems.

The proposed methodology offers several advantages over existing methods, such as reduced conduction losses, maintained power factor, low cost, low voltage stress with high gain, and improved power quality for BEV chargers.

$$Power\ Factor = \frac{I_{rms(1)}}{I_{rms}} \cdot \cos\theta \qquad (3)$$

I_{rms} – RMS value of the current component.

THD is given by

$$THD = \sqrt{\frac{\sum_{n \neq 1} I_n^2}{I_1^2}} \qquad (2)$$

Then, PF is given by

$$PF = \sqrt{\frac{1}{1+THD^2}} \qquad (3)$$

[10] In modern power electronics, AC-DC power supplies are essential for converting alternating current (AC) from the mains into direct current (DC) for a variety of applications. However, these power supplies often introduce significant harmonic distortion into the input current waveform. This not only breaches international standards like IEC 1000-3-2 but also negatively impacts the overall power quality and system efficiency.

To mitigate these issues, power factor correction (PFC) techniques are implemented in AC-DC power supplies. The main goal of PFC is to shape the input current waveform so that it is sinusoidal and in phase with the input voltage. This alignment improves the power factor and minimizes harmonic distortion, ensuring compliance with standards and enhancing the efficincy and reliability of the system.

1.4 Classification of Power Factor Correction Techniques

SSPFC converters and isolated DC-DC conversion functions into a single power converter topology. This approach simplifies the overall system design, reduces component count. Several single-phase and three-phase SSPFC converters have been proposed in the literature, with three-phase converters being preferred for higher power applications due to their better performance and efficiency.

Modular Implementation: Some converters are implemented with three separate AC-DC single-stage modules, increasing cost and introducing synchronization issues between the modules.

High Voltage Ratings: In certain topologies, the switches and bulk capacitors must be rated for very high voltages, as they are exposed to extreme voltage levels during operation.

Complex Control Strategies: Certain converter topologies, such as resonant-type converters, require sophisticated and non-standard control techniques, including variable switching frequency control methods, which add complexity to the system.

Input Current Ripple: Converters with discontinuous input current waveforms exhibiting high peak values require large input filters to mitigate the significant input current ripple.

2 Existing Methods

The transition towards electric vehicles is not merely a technological shift; it represents a paradigm shift in our approach to mobility, one that prioritizes sustainability, energy efficiency, and environmental stewardship. However, the path to fully incorporating transportation electrification is not without its challenges. Researchers, engineers, and policymakers must collaborate to address critical obstacles and develop effective control strategies to seamlessly integrate EVs into existing distribution systems.

[11] One of the key challenges associated with the widespread adoption of EVs lies in addressing power quality issues related to the charging process of their battery packs. Unlike conventional vehicles that rely on fossil fuels, EVs derive their traction force from rechargeable batteries, which must be replenished through a charging process facilitated by an AC-DC converter, commonly known as an EV charger. The architecture of these chargers typically comprises a boost converter at the front-end stage, followed by an isolated converter in the subsequent stage.

[12] The performance characteristics of an EV charger, such as regulated output voltage and output current, are primarily determined by the efficiency and effectiveness of the DC-DC converter stage. To enhance the overall performance and power density of EV chargers, researchers have proposed various topologies and control strategies, including interleaved and zero-voltage switching (ZVS) power factor correction (PFC) converters. These advanced converter designs offer advantages such as reduced inductor size and minimized output current ripple, contributing to improved efficiency and compactness. However, these solutions often come with trade-offs, such as increased current stress on the switching devices in the case of interleaved PFC converters, necessitating careful consideration and optimization.

[13] As the adoption of EVs continues to gain momentum, a notable shift has occurred in the battery technologies employed. The transition from traditional nickel-metal hydride batteries to lithium-ion variants has become prevalent, driven by the latter's superior energy storage capacity and higher power delivery capabilities. Consequently, most modern EV chargers are designed specifically to cater to the unique charging requirements of lithium-ion battery packs, ensuring optimal performance and longevity.

[14] Beyond the technical challenges associated with battery charging, the widespread adoption of electric vehicles presents a multitude of infrastructural and regulatory hurdles that must be addressed. Developing efficient and high-power charging infrastructure is crucial to support the growing demand for EVs and alleviate range anxiety, a common concern among potential EV adopters. This necessitates the establishment of a robust network of charging stations, strategically located and equipped with cutting-edge charging technologies to minimize downtime and maximize convenience for EV users.

Moreover, the integration of EVs with existing distribution systems poses significant challenges. As the number of EVs on the road increases, the demand for electricity will surge, potentially straining the existing electrical grid infrastructure. This underscores the need for proactive measures to reinforce and modernize the distribution systems, ensuring they can handle the additional load while maintaining reliability and resilience.

Overcoming these multifaceted challenges requires a collaborative effort involving researchers, industry stakeholders, and regulatory bodies. Researchers must continue to explore innovative solutions, pushing the boundaries of technology to develop more efficient and reliable charging systems, advanced battery technologies, and intelligent energy management strategies. Industry stakeholders, including automakers, charging infrastructure providers, and utility companies, must work in tandem to establish standardized charging protocols, ensuring interoperability and seamless integration across different EV models and charging stations.

Furthermore, regulatory bodies play a crucial role in setting standards, guidelines, and incentives to accelerate the adoption of electric vehicles and the development of supporting infrastructure. This includes implementing policies that encourage the deployment of renewable energy sources, promoting the establishment of accessible charging networks, and providing financial incentives to encourage consumers and businesses to embrace electric mobility.

By addressing power quality issues related to battery charging, developing efficient and high-power charging infrastructure, and effectively integrating EVs with existing distribution systems, we can pave the way for a sustainable transportation future. This transition will not only contribute to reducing greenhouse gas emissions and mitigating the impact of climate change but also foster energy independence, promote technological innovation, and create new economic opportunities.

The path towards sustainable mobility through electric vehicles is not without its challenges, but the potential benefits are far-reaching and profound. By embracing this transition and overcoming the associated hurdles through collaborative efforts, we can create a more environmentally conscious, energy-efficient, and sustainable transportation ecosystem, ultimately contributing to a healthier planet for future generations.
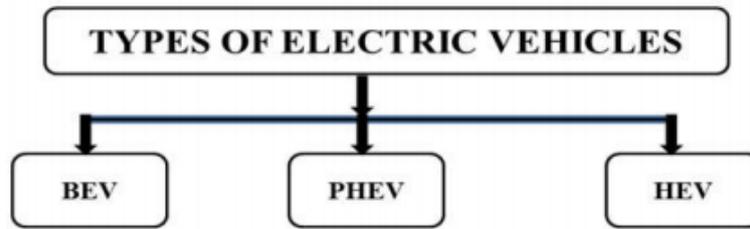

Fig 1: Classification of EV

There are three main types of electric vehicles (EVs), they are classified in the table below:

Table1.1: Types of Electric Vehicles

Type	Description	Energy Source
BEV (Battery Electric Vehicle)	Fully electric vehicle powered solely by a rechargeable battery pack. No gasoline engine.	Electricity (battery)
PHEV (Plug-in Hybrid Electric Vehicle)	Has a rechargeable battery pack and a gasoline engine. Can be powered by electricity or gasoline.	Electricity (battery) and gasoline
HEV (Hybrid Electric Vehicle)	Has a gasoline engine and an electric motor/battery. The battery charges through regenerative braking, not by plugging in.	Gasoline and electricity (from regenerative braking)

3   Proposed System

To develop an improved power factor correction (PFC) converter design for battery electric vehicle (BEV) charging applications. Specifically, a non-isolated Zeta converter topology is modified to reduce switch voltage stresses.

The transition towards a more sustainable transportation future has been accelerated by the rapid adoption of battery electric vehicles (BEVs). As the demand for these environmentally friendly vehicles continues to grow, the need for efficient and reliable charging solutions has become increasingly paramount.

Conventional PFC converters, such as the widely used boost topology, have served their purpose well. However, they are not without limitations, prompting researchers and engineers to explore alternative converter designs that can address these shortcomings and further enhance the performance of BEV charging systems.

Among the promising alternatives is the Zeta converter topology, a buck-boost converter that offers several advantages over conventional boost These characteristics make the Zeta converter well-suited for optimizing power quality in BEV charging applications.

However, despite its potential benefits, conventional Zeta converters exhibit a significant drawback: high voltage stresses across their switching devices. This issue can compromise the reliability and lifespan of the converter components, ultimately impacting the overall performance and durability of the BEV charging system.

Recognizing this challenge, researchers have embarked on a quest to develop an improved Zeta converter design that addresses the high voltage stress issue while retaining the topology's inherent advantages. The proposed solution involves modifying the converter's input side circuitry to clamp the voltage across the switching devices at the input voltage level.

By addressing the high voltage stress issue, this converter topology not only enhances the reliability and extends the lifetime of the components but also improves the overall efficiency and cost-effectiveness of the BEV charging system.

Moreover, the proposed design retains the inherent advantages for the better dynamic response in DCM, tighter voltage regulation, and lower output ripple. These characteristics contribute to optimizing power quality, ensuring efficient and reliable charging operations for BEVs. The developed non-isolated Zeta PFC converter with reduced switch stresses aims to enhance power quality for BEV charging applications. This informs better charger design with optimized performance and durability.
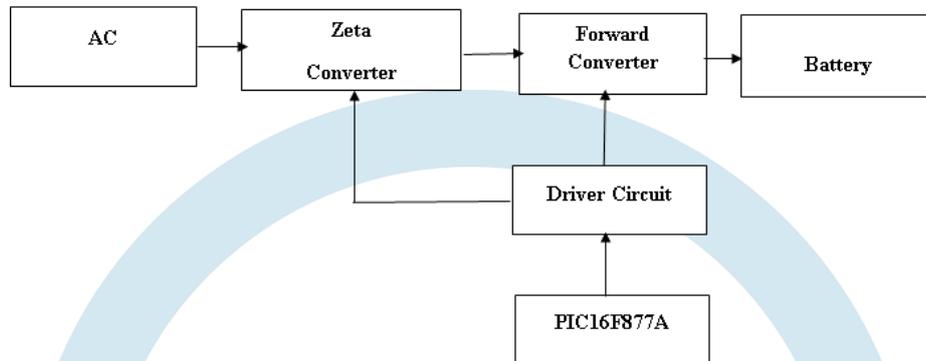

Fig 2: block diagram

The block diagram presented here illustrates a power conversion system designed for battery electric vehicle (BEV) charging applications. It consists of several key components working in tandem to efficiently convert alternating current (AC) from the grid into a regulated direct current (DC) output suitable for charging the battery pack of an electric vehicle.

At the heart of this system lies the Zeta Converter, a versatile DC-DC converter topology that offers several advantages over traditional boost converters commonly used in power factor correction (PFC) circuits. The Zeta Converter acts as a buck-boost converter, providing the ability to step up or step down the input voltage as required. This flexibility is particularly useful in BEV charging applications, where the battery voltage can vary significantly depending on the state of charge.

One of the key strengths of the Zeta Converter is its ability to maintain a continuous input current, which helps reduce electromagnetic interference (EMI) and eliminates the need for an additional input filter. Additionally, the Zeta Converter offers better dynamic response in discontinuous conduction mode (DCM), tighter voltage regulation, and lower output ripple compared to traditional boost converters.

However, conventional Zeta Converters often suffer from high voltage stresses across their switching devices, which can compromise reliability and increase component costs. To address this limitation, the proposed system incorporates a modified Zeta Converter topology that effectively clamps the voltage across the switching devices to the input voltage level. This innovative approach reduces the voltage stress on the switches, enabling the use of lower-voltage-rated components, ultimately improving efficiency, reliability, and cost-effectiveness.

The Driver Circuit block in the diagram represents the control and gate driving circuitry responsible for generating the appropriate switching signals for the power converters. This component plays a critical role in ensuring accurate and efficient operation of the converters, enabling precise control over the output voltage and current characteristics.

At the heart of the control system lies the PIC16F877A microcontroller, a powerful and versatile device capable of executing complex algorithms and control strategies. This microcontroller is responsible for implementing the overall system control, including monitoring the input and output parameters, managing the switching sequences, and implementing any necessary protection or fault-handling mechanisms.

By combining the modified Zeta Converter topology with the Forward Converter and the advanced control capabilities of the PIC16F877A microcontroller, this power conversion system aims to provide an efficient, reliable, and cost-effective solution for BEV charging applications. The system's ability to maintain a high power factor, reduce harmonic distortion, and provide galvanic isolation ensures optimal power quality and

safety, while the reduced voltage stress on the switching devices enhances overall system reliability and longevity.

Moreover, the modular nature of this design allows for scalability and adaptability, enabling the system to be tailored to various input voltage ranges, output power requirements, and specific charging configurations. This flexibility is crucial in the rapidly evolving landscape of electric vehicle technology, where charging standards and battery chemistries are continually evolving.

Overall, the block diagram represents a comprehensive and innovative approach to addressing the challenges of BEV charging, combining advanced power electronics topologies, control strategies, and microcontroller-based intelligence to deliver a high-performance, efficient, and reliable charging solution for electric vehicles.

Fig 3: Prototype model

3.1 The Zeta converter operates in two different modes:

Mode 1: Switch is ON (closed), the diode is OFF.

L1, L2- draws voltage from the source voltage Vs, In this mode the Inductors are charged by the voltage source Vs.
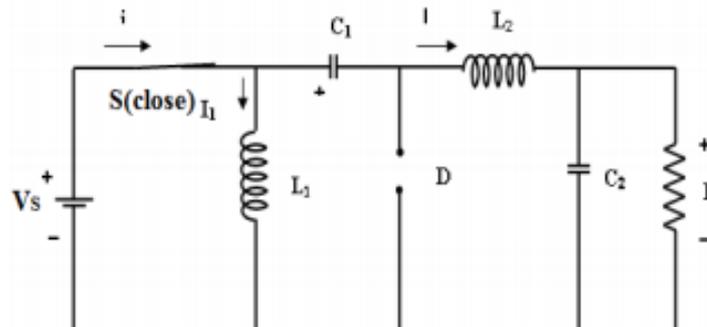

Fig 4: Equivalent circuit of converter (switch ON)

Mode 2: When the switch is OFF, the diode is ON. In this mode, the energy stored in inductor L2 is transferred to the load R. This is called the discharging mode, where the energy stored in the inductors is released to the load.
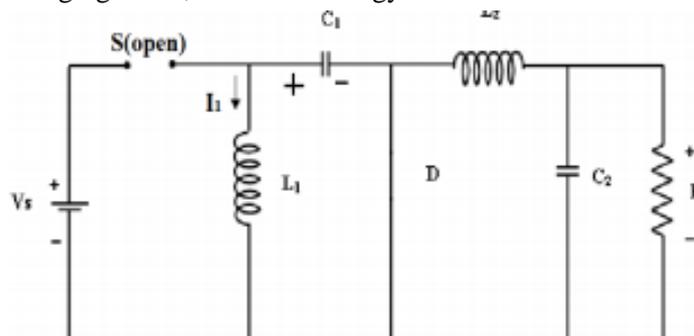

Fig 5: Equivalent circuit of converter (switch OFF)

The proposed methodology involves modifying the input side of the conventional Zeta converter to clamp the voltage across the switching device at the input voltage level. This modification reduces the voltage stress on the switching device, which is typically higher than the input voltage in the conventional Zeta converter topology.

By clamping the voltage across the switching device to the input voltage level, the proposed methodology aims to mitigate the issue of high voltage stress, which is a disadvantage of conventional Zeta converters. This voltage stress reduction can lead to improved reliability and efficiency of the converter.

The proposed methodology offers several advantages over existing methods, such as reduced conduction losses, maintained power factor, low cost, low voltage stress with high gain, and improved power quality for BEV chargers. By addressing the disadvantages of conventional Zeta converters, such as high-power rating, more voltage stress, and low efficiency, the proposed methodology aims to provide a more efficient and cost-effective solution for BEV charger applications.

This modification, combined with the advantages of the Zeta converter topology and the inclusion of a forward converter, aims to improve power quality, efficiency, and cost-effectiveness in BEV charger applications.

- Advantages of the Proposed System:
- Conduction losses are reduced.
- Power factor is maintained.
- Low cost, low voltage stress with high gain.

The proposed methodology involves modifying the input side of the conventional Zeta converter to clamp the voltage across the device at the input voltage, reducing switch voltage stress. This modification, along with the advantages of the Zeta converter, such as better dynamic response in DCM, good voltage regulation, and low output ripple, aims to improve power quality in BEV chargers while maintaining a low cost and high efficiency.

4   Simulations and Analysis

We use MATLAB, a powerful software tool widely used for simulations and analysis in various engineering fields, including power electronics and electrical systems. In the proposed methodology with reduced switch voltage stress for BEV chargers, MATLAB simulations play a crucial role in verifying the system's performance and analyzing its behaviour under different operating conditions.

The MATLAB simulations for the proposed Zeta converter system can be carried out using the Sim-Power-Systems library, which is specifically designed for modelling and simulating power systems and power electronics circuits. This library provides a wide range of pre-built component models, including various converter topologies, transformers, machines, and control systems.
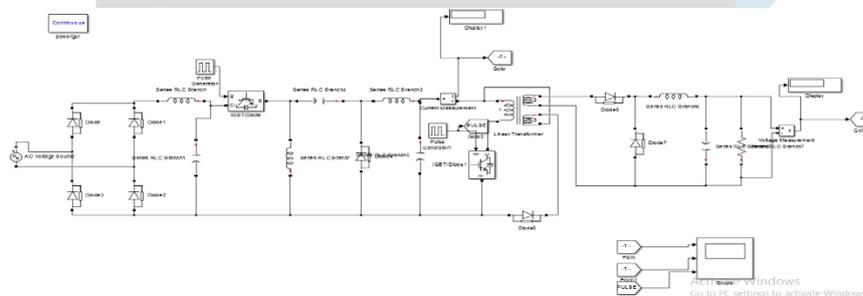

Fig 6: simulation of circuit diagram

To simulate the proposed Zeta converter system, the first step is to create a simulation model in the MATLAB/Simulink environment. This can be done by dragging and dropping the required components from the Sim-Power-Systems library into the Simulink model window and connecting them according to the circuit diagram of the proposed system.

The simulation model should include the modified Zeta converter topology with the input side modification for voltage stress reduction, as well as the forward converter for providing an isolated and controlled output voltage. Additionally, the model should incorporate the necessary control systems, such as pulse-width modulation (PWM) generators, for controlling the switching of the power electronic devices.

Once the simulation model is set up, various parameters and operating conditions can be defined, such as the input voltage, load conditions, switching frequencies, and control strategies. MATLAB provides a user-friendly interface for setting these parameters and running the simulations.

During the simulations, MATLAB can capture and display various waveforms and data, including input and output voltages, currents, power factors, and efficiency. These waveforms and data can be analyzed to evaluate the performance of the proposed system under different operating conditions and to verify its compliance with the design specifications.
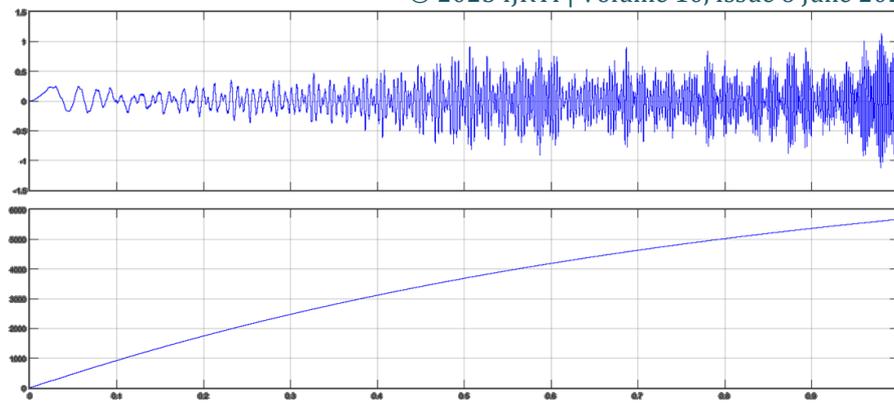
Fig 7: motor scope and back EMF

Additionally, MATLAB offers powerful analysis tools, such as Fourier analysis, to examine the harmonic content of the output waveforms and assess the power quality of the system. This is particularly important for BEV charger applications, where maintaining a high power quality is crucial for efficient and reliable operation.
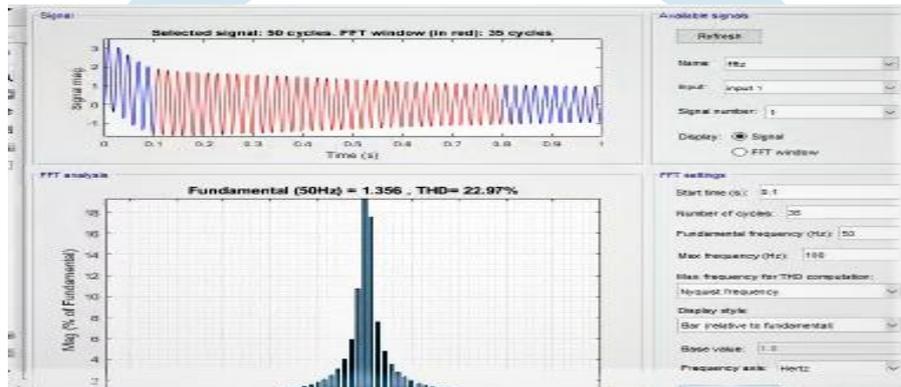

Fig 8: THD level ==22.9 or .229

One of the key advantages of MATLAB simulations is the ability to perform parametric studies and optimization. By varying different parameters, such as component values, switching frequencies, or control strategies, engineers can explore the design space and identify optimal configurations that maximize the system's performance, efficiency, and power quality.
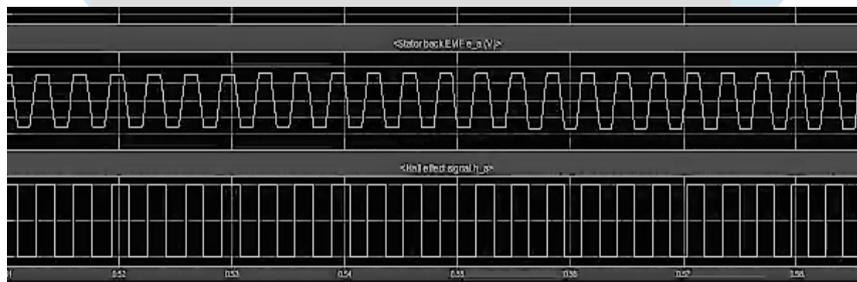

Figure 9: Stator back EMF gate pulse

Furthermore, MATLAB simulations can be used to investigate the transient behavior of the proposed system, such as start-up, load changes, and fault conditions. This information is essential for designing effective control strategies and protection mechanisms, ensuring the safe and reliable operation of the BEV charger.

Overall, MATLAB simulations and analysis play a vital role in the development and evaluation of the proposed non-isolated Zeta PFC converter with reduced switch voltage stress for BEV chargers. These simulations allow engineers to verify the system's performance, analyze its behaviour under different operating conditions, optimize the design parameters, and investigate transient and fault scenarios, ultimately leading to a more robust and efficient BEV charger solution.

6   Conclusion

The proposed non-isolated Zeta power factor correction (PFC) converter with reduced switch voltage stress offers an effective solution for enhancing power quality in battery electric vehicle (BEV) chargers. By modifying the input circuitry of the traditional Zeta converter, the design clamps the voltage across switching devices to the input voltage level, significantly reducing voltage stress. This reduction allows the use of lower-voltage-rated, cost-effective switching devices with lower conduction losses, boosting component reliability and lifespan while improving the overall efficiency and cost-effectiveness of the BEV charger system. The Zeta converter topology offers advantages such as superior dynamic response in discontinuous conduction mode (DCM), tighter voltage regulation, and lower output ripple, making it ideal for optimizing power quality in BEV charging applications. The integration of these benefits with voltage stress reduction results in a comprehensive solution for maintaining high power quality and

ensuring efficient, reliable operation. MATLAB simulations and analysis have been crucial in verifying the system's performance and behavior under various conditions, including waveform capture, Fourier analysis for harmonic content, and parametric studies, providing valuable insights for converter design and optimization. Furthermore, incorporating a forward converter enables an isolated, controlled output voltage, suitable for diverse BEV charger applications with varying voltage requirements. Overall, the proposed non-isolated Zeta PFC converter with reduced switch voltage stress represents a significant advancement in BEV charger technology. By addressing conventional converter limitations and leveraging Zeta architecture advantages, this innovative solution promotes the development of efficient, reliable, and cost-effective BEV chargers, supporting the widespread adoption of electric vehicles and a sustainable transportation future.

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