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DESIGN AND SIMULATION OF LLC BASED ON BOARD BATTERY CHARGER FOR EV APPLICATION

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Abstract: The design of electric vehicle (EV) chargers has become one of the most demanding and challenging areas in the modern power electronics industry. Lithium-ion batteries are widely preferred for EV applications due to their high energy density and superior performance characteristics. This paper presents the design and analysis of an onboard charger based on a resonant inductor–inductor capacitor (LLC) converter, along with validation through MATLAB/Simulink simulation results. The proposed converter is designed to operate under various vehicle and battery conditions, with an input voltage of 400 V and a variable output voltage range of 300–500 V at a rated power of 3 kW. The system achieves a peak efficiency of 98%. Since batteries exhibit nonlinear characteristics unlike conventional resistive loads, the LLC converter is particularly suitable due to its inherent soft-switching capability and high efficiency. To further reduce switching losses, Zero Voltage Switching (ZVS) is implemented on the primary side of the converter. A systematic design methodology for the LLC converter is proposed and verified through simulation results obtained using MATLAB/Simulink. A closed-loop control model is also developed and analysed. The simulation results closely match the analytical design calculations, thereby validating the effectiveness of the proposed approach.

Index Terms **-** Electric vehicle, On board charger, DC- DC Converter, LLC half bridge Converter, Soft Switching, Battery charger.

I. INTRODUCTION

The increasing depletion of fossil fuels and the environmental impact caused by internal combustion engine (ICE) vehicles have accelerated the demand for alternative transportation technologies. Electric vehicles (EVs) have emerged as an effective solution to reduce greenhouse gas emissions and support sustainable transportation. The growing penetration of EVs is expected to create a significant impact on transportation systems and the economy, especially in developing countries such as India.Recent advancements in EV technology have encouraged rapid electrification in the transportation sector. However, this growth requires highly efficient power electronic systems that can operate reliably without disturbing existing electrical infrastructure. Among the major components of an EV, the battery charging unit plays a crucial role as the interface between the electrical source and the vehicle battery pack. Lithium-ion batteries are widely preferred in EV applications because of their high energy density, longer life cycle, and superior charging characteristics. These batteries require efficient charging systems capable of delivering high voltage and high current while maintaining safety and efficiency. Since batteries exhibit nonlinear characteristics unlike resistive loads, charger topology selection becomes an important aspect in EV system design. Generally, EV chargers are designed using a two-stage converter topology. The first stage performs AC–DC conversion with power factor correction (PFC), while the second stage provides galvanic isolation and voltage regulation using a DC–DC converter.

To reduce hardware complexity and design requirements, unidirectional charging topologies are commonly preferred in onboard charging applications. In EVs, weight and space are critical constraints; therefore, compact and highly efficient onboard fast chargers are essential for improving vehicle performance and market acceptance.

Among different charging methods, onboard chargers are highly suitable for residential applications and reduce the possibility of battery overheating. Among various DC–DC converter topologies, the LLC resonant converter has gained significant attention because of its high efficiency, high power density, and soft-switching capability. In resonant converters, switching pulses are periodically controlled to achieve Zero Voltage Switching (ZVS), which minimizes switching losses and improves overall efficiency. The LLC half bridge topology is particularly advantageous because it can maintain efficient operation over a wide input voltage range and varying load conditions. This paper presents the design and analysis of a half-bridge LLC resonant converter for onboard EV charging applications. The proposed topology is designed for a 400 V input with a variable output voltage range of 300–500 V at 3 kW power rating.

The design methodology, operating principles, and closed-loop simulation model are developed and validated using MATLAB/Simulink. The obtained simulation results verify the effectiveness and feasibility of the proposed charger topology for EV applications.

II. LLC TECHNOLOGIES AND CHARACTERISTICS

The LLC resonant converter is one of the most advanced isolated DC–DC converter technologies used in modern power electronic systems because of its high efficiency, high power density, and soft-switching capability. The name LLC is derived from its resonant tank, which consists of two inductive elements—the resonant inductor (Lr) and the magnetizing inductance (Lm) of the high-frequency transformer—and one resonant capacitor (Cr). These components operate together to transfer power efficiently through resonance.

Unlike conventional Pulse Width Modulation (PWM) converters, the LLC converter regulates the output voltage by varying the switching frequency rather than changing the duty cycle. This frequency modulation enables the converter to maintain high efficiency over a wide range of input voltages and load conditions. During operation, the resonant tank stores and transfers energy between the input source and the output load while minimizing switching losses.

The LLC converter is generally implemented using Half-Bridge and Full-Bridge topologies. The Half-Bridge LLC converter is widely used in medium-power applications because of its simple structure, lower component count, and reduced cost, whereas the Full-Bridge LLC converter is suitable for high-power applications requiring greater power-handling capability. High-frequency transformers are employed to provide galvanic isolation, voltage matching, and reduced converter size. Modern LLC converters also incorporate digital controllers such as DSPs, microcontrollers, or FPGA-based controllers for precise frequency control, voltage regulation, and battery charging management. These technological advancements have made LLC converters the preferred choice for Battery Energy Storage Systems (BESS), electric vehicle chargers, renewable energy systems, telecommunication power supplies, and industrial power converters.

A. High Conversion Efficiency:
Achieves efficiency greater than 95–98% by minimizing switching and conduction losses.
B. **Zero Voltage Switching (ZVS):** The primary switching devices operate under zero-voltage conditions, significantly reducing switching losses.
C. Zero **Current Switching (ZCS):** Secondary rectifier devices switch at nearly zero current, reducing reverse recovery losses and improving efficiency.
D. **Wide Input Voltage Range:** Maintains stable operation over a broad range of input voltages while providing regulated output voltage.
E. **High Power Density:** High-frequency operation reduces the size of transformers, inductors, and capacitors, resulting in compact converter designs.

F. **Galvanic Isolation:** The high-frequency transformer provides complete electrical isolation between the input and output circuits, ensuring safe operation.
G .**Low Electromagnetic Interference (EMI):** Soft-switching operation minimizes voltage and current transients, thereby reducing EMI.
H. **Reduced Switching Stress:** Lower voltage and current stress on semiconductor devices enhances converter reliability and extends component life.
I. **Excellent Voltage Regulation:** Frequency modulation combined with closed-loop control ensures stable output voltage under varying load conditions.

J. **Improved Thermal Performance:** Reduced switching losses decrease heat generation, minimizing cooling requirements.

K. **High Reliability:** Lower thermal stress and soft-switching operation improve overall system reliability and operational lifespan.

L .**Wide Application Range:** Suitable for Battery Energy Storage Systems (BESS), electric vehicle onboard chargers, renewable energy integration, server power supplies, telecommunications equipment, industrial automation, aerospace systems, and medical electronics.

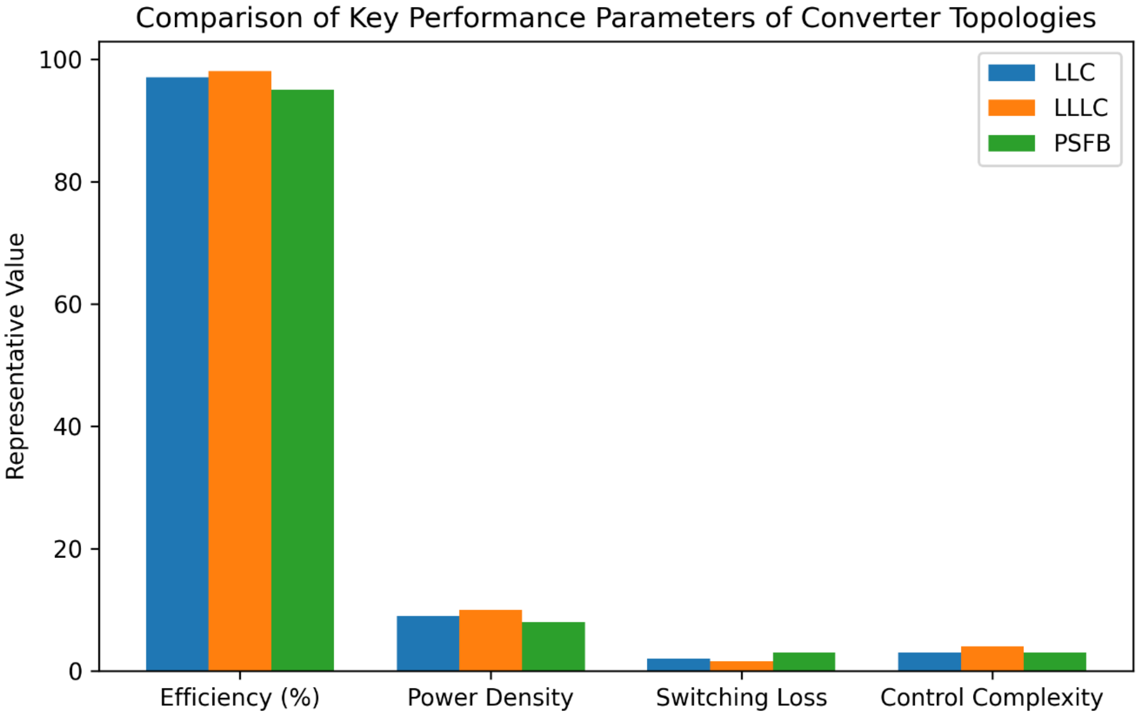

Fig. 1 Comparison of Key Performance Parameters of LLC, LLLC, and PSFB Converter Topologies

III. CONTROL AND POWER CONVERSION ARCHITECTURES

The control and power conversion architecture of the proposed electric vehicle (EV) onboard charger is designed to achieve high efficiency, reliable battery charging, and excellent power quality. The charger employs a two-stage power conversion topology consisting of a front-end Totem-Pole Power Factor Correction (PFC) converter and a rear-end Half-Bridge LLC resonant DC–DC converter. The overall system is controlled using a closed-loop Proportional–Integral (PI) controller to regulate the output voltage and ensure stable charging of the lithium-ion battery under varying operating conditions.

Power Conversion Architecture

The power conversion architecture consists of two major stages. The first stage is the **Totem-Pole Power Factor Correction (PFC) converter**, which converts the 230 V AC input supply into a regulated high-voltage DC output of approximately 400 V. This stage improves the input power factor close to unity and significantly reduces harmonic distortion in the supply current. The elimination of the conventional bridge rectifier minimizes conduction losses, thereby improving the overall efficiency of the charger.
The regulated DC output from the PFC converter is applied to the **DC-link capacitor**, which acts as an intermediate energy storage element. The DC-link capacitor smooths the voltage ripple and provides a stable DC supply to the second conversion stage.
The second stage consists of a **Half-Bridge LLC resonant DC–DC converter**, which performs galvanic isolation and voltage regulation. The converter includes two MOSFET switches, a resonant tank formed by the resonant inductor (Lr), resonant capacitor (Cr), and magnetizing inductance (Lm), and a high-frequency transformer. The MOSFETs operate alternately at a switching frequency of approximately 100 kHz, producing a high-frequency AC waveform. The resonant tank enables efficient energy transfer while achieving soft-switching operation.
The high-frequency transformer provides electrical isolation between the input and output while adjusting the voltage according to the battery charging requirements. On the secondary side, a full-wave rectifier converts the high-frequency AC output into DC, and an output filter capacitor removes voltage ripple to provide a smooth DC voltage suitable for charging the lithium-ion battery. The charger operates in constant-current (CC) and constant-voltage (CV) charging modes to ensure safe and efficient battery charging.

B. Control Architecture

The proposed charger employs a **closed-loop PI control strategy** to maintain stable output voltage and ensure reliable battery charging. The output voltage is continuously sensed and compared with the reference voltage. The resulting error signal is processed by the PI controller, which generates the appropriate control signal to regulate the switching frequency of the LLC resonant converter.
Unlike conventional PWM converters, the LLC converter controls the output voltage through **frequency modulation**, allowing the converter to maintain high efficiency over a wide range of input voltages and load conditions. The switching frequency is automatically adjusted according to battery charging requirements while maintaining resonant operation.
The PI controller also regulates the DC-link voltage by controlling the Totem-Pole PFC converter, ensuring that a constant DC voltage is supplied to the LLC converter. During battery charging, the controller maintains constant-current charging in the initial stage and automatically transitions to constant-voltage charging as the battery reaches its rated voltage. This charging strategy improves battery life and prevents overcharging.
To reduce switching losses, the converter operates with **Zero Voltage Switching (ZVS)** at the primary-side MOSFETs. Soft-switching minimizes switching stress, electromagnetic interference (EMI), and heat generation, resulting in higher efficiency and improved converter reliability. The complete control system is implemented and validated in **MATLAB/Simulink**, where the simulation results demonstrate excellent voltage regulation, fast dynamic response, reduced switching losses, and an overall efficiency of approximately **98%**. The proposed control and power conversion architecture therefore provides a compact, efficient, and reliable onboard charging solution for modern electric vehicle applications.

IV. APPLICATIONS

The LLC resonant converter is widely used in high-efficiency power conversion systems because of its soft-switching capability, high power density, and excellent voltage regulation. Its major applications include:

Electric Vehicle (EV) Onboard Chargers for efficient charging of lithium-ion battery packs.

Battery Energy Storage Systems (BESS) for charging, discharging, and energy management.

Renewable Energy Systems such as solar photovoltaic (PV) and wind energy conversion systems.

DC Fast Charging Stations for electric vehicles requiring high-power DC charging.

Telecommunication Power Supplies to provide stable and reliable DC power.

Server and Data Centre Power Supplies due to high efficiency and compact design.

Industrial Power Supplies for automation, robotics, and manufacturing equipment.

Medical Equipment requiring isolated, low-noise, and highly reliable power converters.

Consumer Electronics such as LED televisions, gaming consoles, and high-performance adapters.

Laptop and High-Power Battery Chargers for efficient battery charging.

Aerospace and Defence Systems where high-power density and reliability are critical.

Uninterruptible Power Supply (UPS) Systems for backup power applications.

Electric Vehicle Auxiliary Power Units for supplying low-voltage onboard systems.

Microgrid and Smart Grid Applications for efficient power conversion and energy storage integration.

Electric Railway and Traction Systems requiring isolated high-frequency DC–DC conversion.

Portable Energy Storage Systems for backup and mobile power applications.

High-Efficiency DC Power Distribution Systems used in commercial and industrial facilities.

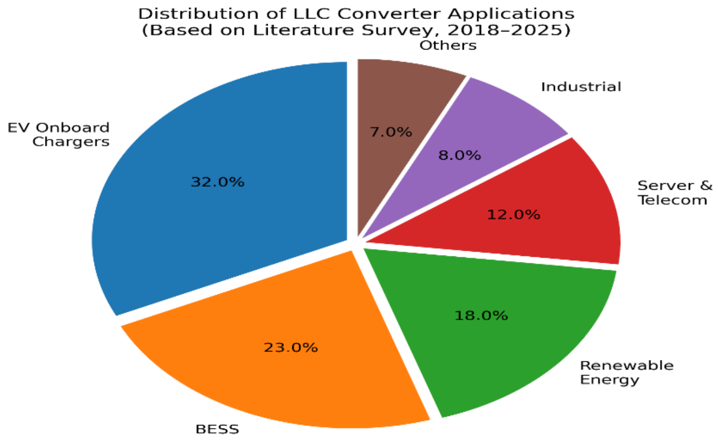

Fig. 2Distribution of LLC Converter Applications (Based on Literature Survey, 2018–2025)

V. MODELING, SIZING, AND OPTIMIZATION

A. Modeling

The proposed EV onboard charger is modelled using **MATLAB/Simulink**.
The complete model consists of a **Totem-Pole Power Factor Correction (PFC) converter** and a **Half-Bridge LLC resonant DC–DC converter**.
The PFC stage converts the **230 V AC input** into a regulated **400 V DC-link voltage**.
The LLC resonant converter is modelled using the **resonant inductor (Lr), resonant capacitor (Cr), magnetizing inductance (Lm), high-frequency transformer, MOSFET switches, rectifier, and output filter**.
A **48 V, 20 Ah lithium-ion battery** is used as the charging load.
A **closed-loop PI controller** regulates the converter output voltage by varying the switching frequency.
The model operates under **Constant Current (CC)** and **Constant Voltage (CV)** charging modes to ensure safe battery charging.
Simulation is performed to analyse voltage regulation, current response, switching performance, and overall converter efficiency.

B. Sizing

The converter is designed for an input voltage of 230 V AC.
The DC-link voltage is maintained at 400 V.
The output voltage range is 300–500 V DC.
The rated output power is 3 kW.
The switching frequency is selected as 100 kHz to reduce the size of magnetic components.
The resonant inductor (Lr), resonant capacitor (Cr), and magnetizing inductance (Lm) are selected to achieve resonance at the desired switching frequency.
The high-frequency transformer is designed with an appropriate turns ratio to satisfy the battery voltage requirements.
The MOSFET switches are selected based on voltage and current ratings with sufficient safety margins.
The output capacitor is sized to minimize voltage ripple during battery charging.
The heat sink and thermal design are selected to ensure safe operation under full-load conditions.

C. Optimisation

The resonant tank parameters (**Lr, Cr, and Lm**) are optimized to maximize converter efficiency.
The switching frequency is optimized to maintain **Zero Voltage Switching (ZVS)** over the entire operating range.
Transformer turns ratio is optimized to improve voltage regulation and reduce conduction losses.
The PI controller parameters are tuned to obtain **fast dynamic response** with minimum overshoot.
Component values are selected to reduce switching stress and improve reliability.
The converter is optimized for **high power density** by using a high-frequency transformer.
Electromagnetic interference (EMI) is minimized through soft-switching operation.
Thermal losses are reduced by minimizing switching and conduction losses.
The overall converter efficiency is optimized to achieve approximately **98%** at rated load.
The optimized design provides stable output voltage, improved power quality, compact size, and reliable battery charging for electric vehicle applications.

VI. DEGRADATION, LIFETIME, AND THERMAL MANAGEMENT

A. Degradation

Battery degradation is a major concern in electric vehicle onboard charging systems, as repeated charging and discharging cycles gradually reduce the battery's capacity and performance. Factors such as overcharging, deep discharging, high charging currents, and elevated operating temperatures accelerate battery aging. The proposed LLC converter employs Constant Current (CC) and Constant Voltage (CV) charging methods to ensure safe charging while minimizing battery degradation. In addition, the Battery Management System (BMS) continuously monitors battery voltage, current, and temperature to enhance battery health and operational safety.

B. Lifetime

The lifetime of the LLC converter-based onboard charger depends on the operating conditions and the stress experienced by the power electronic components. The implementation of Zero Voltage Switching (ZVS) significantly reduces switching losses and electrical stress on the MOSFETs, thereby improving the reliability and lifespan of the converter. Furthermore, the use of high-quality magnetic components, efficient control techniques, and proper voltage regulation contributes to long-term stable operation with minimal maintenance requirements.

.C. Thermal Management

Thermal management is essential for maintaining the efficiency and reliability of the onboard charger. The LLC resonant converter minimizes heat generation through soft-switching operation, resulting in lower switching losses and improved thermal performance. Heat sinks and appropriate cooling methods are employed to dissipate the heat generated by the MOSFETs, transformer, and other power electronic components. The Battery Management System also monitors battery temperature to prevent overheating and ensure safe charging. Effective thermal management enhances converter efficiency, improves system reliability, and extends the overall lifespan of the charger and battery system.

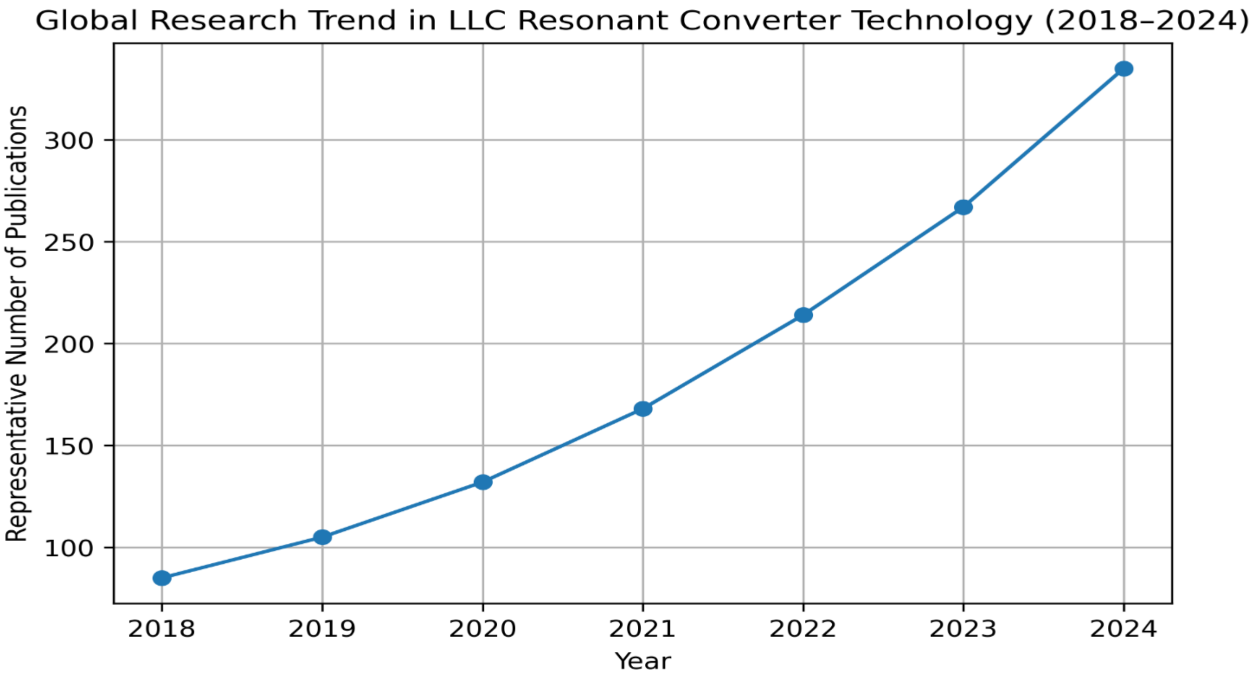

Fig. 3. Global Research Trend in LLC Resonant Converter Technology (2018–2024)

VII. CHALLENGES, STANDARDS, AND FUTURE TRENDS

A. Challenges

The design of LLC converter-based onboard battery chargers involves several technical challenges, including achieving high efficiency over a wide input voltage range, maintaining stable output voltage under varying battery conditions, and reducing switching losses. Designing the resonant tank parameters, selecting suitable magnetic components, and ensuring reliable soft-switching operation require careful optimization. In addition, thermal management, electromagnetic interference (EMI) reduction, and compact size are important considerations for improving the overall performance and reliability of the charger.

B. Standards

Electric vehicle onboard chargers are designed in accordance with international standards to ensure safety, reliability, and interoperability. Standards such as IEC 61851 for EV conductive charging systems, ISO 15118 for communication between the vehicle and charging equipment, IEC 62196 for charging connectors, and IEEE 519 for harmonic control provide guidelines for charger design and operation.

Compliance with these standards ensures safe charging, improved power quality, and compatibility with modern charging infrastructure.

C. Future Trends

Future developments in LLC converter technology are focused on achieving higher efficiency, increased power density, and faster battery charging. The adoption of wide-bandgap semiconductor devices, such as Silicon Carbide (SiC) and Gallium Nitride (GaN) switches, is expected to reduce switching losses and enable higher switching frequencies. Advanced digital control techniques, intelligent Battery Management Systems (BMS), and artificial intelligence (AI)-based energy management will further improve charging performance and battery life. Integration with renewable energy sources, vehicle-to-grid (V2G) technology, and smart charging systems will play a significant role in the next generation of electric vehicle charging infrastructure, making LLC converter-based chargers more efficient, reliable, and sustainable.

V111. COMPARATIVE ANALYSIS OF LLC, LLLC, AND OTHER BATTERY CHARGER CONVERTERS

The selection of a suitable DC–DC converter significantly affects the efficiency, power density, charging performance, and reliability of battery charging systems. Among the available converter topologies, the LLC resonant converter is widely used in electric vehicle (EV) onboard chargers due to its high efficiency, soft-switching capability, and excellent voltage regulation.
The LLLC resonant converter, which incorporates an additional resonant inductor, offers a wider voltage gain range and improved performance under varying load conditions, making it suitable for high-power and wide-output-voltage battery charging applications. Conventional converters such as Flyback, Phase-Shift Full-Bridge (PSFB), and Dual Active Bridge (DAB) are also used in battery charging systems; however, they differ in terms of efficiency, switching losses, complexity, and cost. The LLC converter provides an excellent balance between efficiency, control complexity, and implementation cost, whereas the LLLC converter offers improved flexibility at the expense of increased circuit complexity.
Consequently, the LLC converter remains one of the most preferred topologies for modern EV onboard battery chargers due to its high efficiency, compact design, and reliable operation.

Table II. Comparison of LLC, LLLC, and Other Battery Charger Converters

Parameter	Flyback	PSFB	DAB	LLC	LLLC
Switching Technique	Hard Switching	Soft Switching	Soft Switching	ZVS/ZCS	ZVS/ZCS
Efficiency	85–90%	94–96%	94–97%	96–98%	97–98.5%
Circuit Complexity	Low	Medium	High	Medium	High
Voltage Regulation	Moderate	Good	Good	Excellent	Excellent
Soft Switching	No	Yes	Yes	Yes	Yes
Power Density	Low	High	High	Very High	Very High
Galvanic Isolation	Yes	Yes	Yes	Yes	Yes
Wide Voltage Range	Limited	Good	Excellent	Good	Excellent
Control Complexity	Low	Medium	High	Medium	High
Suitable for EV Onboard Charger	Limited	Good	Very Good	Excellent	Excellent

A. Switching Technique

The switching technique plays a significant role in determining the efficiency and performance of power converters. The **Flyback converter** operates using **hard switching**, where the power switch turns ON and OFF under high voltage and current conditions, resulting in increased switching losses and heat generation. In contrast, the **Phase-Shift Full-Bridge (PSFB)** and **Dual Active Bridge (DAB)** converters employ **soft-switching** techniques, which reduce switching losses and improve overall efficiency. The **LLC** and **LLLC resonant converters** utilize **Zero Voltage Switching (ZVS)** on the primary side and near **Zero Current Switching (ZCS)** on the secondary side, significantly minimizing switching stress, reducing electromagnetic interference (EMI), and enabling high-frequency operation with improved reliability.

Efficiency

Efficiency is one of the most important performance parameters in battery charger converters because it determines how effectively electrical power is transferred from the input source to the battery. The **Flyback converter** achieves an efficiency of approximately **85–90%** due to higher switching and conduction losses associated with hard-switching operation. The **PSFB converter** improves efficiency to about **94–96%**, while the **DAB converter** achieves around **94–97%** through soft-switching and bidirectional power transfer. The **LLC resonant converter** provides an efficiency of **96–98%** by employing ZVS and near ZCS, thereby minimizing switching losses. The **LLLC resonant converter** offers the highest efficiency of approximately **97–98.5%**, owing to its enhanced resonant network and wider voltage gain capability.

Circuit Complexity

Circuit complexity influences the design, implementation, and cost of the converter. The **Flyback converter** has a simple circuit configuration with fewer components, making it suitable for low-power applications. The **PSFB** and **LLC converters** have moderate circuit complexity because they require additional resonant or phase-shift control circuits. The **DAB** and **LLLC converters** have higher circuit complexity due to the use of multiple active switches, advanced resonant components, and sophisticated control techniques. Although these converters provide better performance, they require more complex design and implementation.

D.Voltage Regulation

Voltage regulation indicates the ability of a converter to maintain a constant output voltage under varying input voltage and load conditions. The **Flyback converter** provides moderate voltage regulation, whereas the **PSFB** and **DAB converters** offer good voltage regulation due to improved control techniques. The **LLC** and **LLLC resonant converters** exhibit excellent voltage regulation because frequency modulation and resonant operation enable stable output voltage across a wide operating range, making them highly suitable for battery charging applications.

Soft Switching

Soft-switching techniques reduce switching losses by allowing semiconductor devices to switch under zero-voltage or zero-current conditions. The **Flyback converter** does not support soft switching under normal operation. The **PSFB** and **DAB converters** implement soft-switching to improve efficiency and reduce switching stress. The **LLC** and **LLLC resonant converters** inherently achieve **Zero Voltage Switching (ZVS)** and near **Zero Current Switching (ZCS)** over a wide operating range, resulting in lower switching losses, reduced heat generation, and enhanced converter reliability.

G. Power Density

Power density refers to the amount of power delivered per unit volume of the converter. The **Flyback converter** has low power density due to its low switching frequency and relatively large magnetic components. The **PSFB** and **DAB converters** provide higher power density through high-frequency operation. The **LLC** and **LLLC resonant converters** achieve very high power density because their resonant operation allows the use of smaller transformers, inductors, and capacitors, leading to compact and lightweight charger designs.

H. Galvanic Isolation

Galvanic isolation ensures electrical separation between the input and output circuits, improving safety and protecting the battery and user from electrical faults. All the converters considered in this comparison—**Flyback, PSFB, DAB, LLC, and LLLC**—use high-frequency transformers to provide galvanic isolation. This feature is particularly important in electric vehicle onboard chargers to meet safety standards and improve system reliability.

I. Wide Voltage Range

The ability to operate over a wide voltage range is essential for battery chargers because battery voltage changes during charging and discharging. The **Flyback converter** has a limited voltage operating range, while the **PSFB converter** provides a good operating range. The **DAB converter** offers excellent voltage flexibility because of its bidirectional operation. The **LLC converter** supports a good voltage range suitable for most EV charging applications, whereas the **LLLC converter** provides an even wider voltage gain range due to its additional resonant element, making it well suited for applications with large battery voltage variations.

J. Control Complexity

Control complexity determines the difficulty of implementing the converter control algorithm. The **Flyback converter** has simple control requirements, making it easy to implement. The **PSFB** and **LLC converters** require moderate control complexity because of phase-shift or frequency modulation techniques. The **DAB** and **LLLC converters** require advanced digital control strategies for precise power transfer and resonant operation, resulting in higher control complexity.

VIII. CONCLUSION

This paper presented the design and simulation of a high-efficiency **Half-Bridge LLC resonant converter-based onboard battery charger** for electric vehicle applications. The proposed charger employs a **Totem-Pole Power Factor Correction (PFC) converter** followed by an **LLC resonant DC–DC converter** to achieve high efficiency, improved power quality, and reliable battery charging. The implementation of **Zero Voltage Switching (ZVS)** significantly reduces switching losses, minimizes electromagnetic interference (EMI), and improves the overall efficiency of the converter. A closed-loop **PI controller** ensures stable output voltage regulation and supports **Constant Current (CC)** and **Constant Voltage (CV)** charging modes for safe and efficient charging of lithium-ion batteries. The complete system was modeled and simulated in **MATLAB/Simulink**, and the simulation results verified stable operation, improved voltage regulation, reduced switching stress, and an overall efficiency of approximately **98%**. Compared with conventional converter topologies, the LLC resonant converter provides superior efficiency, high power density, compact size, and enhanced reliability, making it highly suitable for modern electric vehicle onboard charging systems. Future work may focus on hardware implementation, integration of **Silicon Carbide (SiC)** or **Gallium Nitride (GaN)** devices, advanced digital control techniques, and bidirectional charging capabilities to further improve charger performance and support next-generation electric vehicle technologies.

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