# The Road to Efficiency: Emerging EV Charging Techniques

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**Abstract -** *Compared to hybrid and combustion engine vehicles, electric vehicles have many advantages. However, the market for automobiles has yet to embrace electrified vehicles as widely as anticipated, primarily because of the lack of the fast charging and the issue of driving range anxiety. Additionally, the electric vehicle's onboard charging system is extremely slow and has a restricted power capacity. Therefore, fast charging systems capable of charging an electric vehicle in a few minutes and give it a long enough driving range are necessary for the advancement of the electric vehicle industry. This article aims to explore battery charging systems, as well as current and emerging developments in power electronic devices, converters, and research possibilities. It also provides an overview of the fundamental architectures of high-speed charging systems and assessment of power efficiency converters, along with their comparative analysis. Another challenge is developing high power, highly efficient, low-cost charging systems and their integration with renewable energy sources. This method of charging batteries promises increased energy conversion efficiency with variable power demands, guaranteeing steady and dependable operation that makes it appropriate for a variety of applications, such as renewable resources and electric vehicles.*

***Key Words***: (**Electric Vehicles, Lithium-ion battery, EV chargers, Fast charging, onboard and offboard charging, renewable energy integration**.)

## 1) . INTRODUCTION

Electric vehicle (EV) technology has advanced significantly due to the increasing global demand for sustainable and energy-efficient transportation solutions. Battery charging systems are one of the most important elements of an EV ecosystem since they guarantee effective energy storage and use. Electric vehicles provide several benefits compared to conventional internal combustion engine (ICE) vehicles. including zero tailpipe emissions, reduced dependence on fossil fuels, and superior energy efficiency. As advancements in battery technology, charging infrastructure, and electric drivetrains continue to evolve, EVs are becoming more accessible, practical, and appealing for everyday use. This study aims to explore the advantages of using a PSFB-based battery charging system compared to traditional charging techniques.

About 23% of the world's energy-related CO2 emissions come from the sports industry, and between 2010 and 2015, emissions increased at a pace of 2.5 percent annually. Moreover, internal combustion engine (ICE) vehicles incur higher fuel and maintenance expenses due to regular oil changes, engine upkeep, and mechanical deterioration, unlike electric vehicles (EVs). Whereas EVs transform more than 80% of electrical energy into mechanical power, an ICE's efficiency is normally between 20% and 30%. Furthermore, the combustion and exhaust systems of ICE vehicles produce a considerable amount of noise pollution. The decarbonization of the transportation industry is anticipated to be significantly aided by transportation electrification. Over the past ten years, the market for EVs has grown at a never-before-seen rate. With so many advantages, EVs are becoming the favored option for transportation in the future. Since EVs don't emit tailpipes, they help to mitigate climate change and reduce air pollution. They use energy more efficiently than conventional gasoline-powered automobiles, with efficiency rates of 80%. Since electric vehicles contain fewer moving components, they demand less maintenance and operate without the need for gasoline. To further lessen carbon footprints, they can be charged using solar, wind, or other renewable energy sources. Incentives, tax breaks, and subsidies are provided by numerous governments across the globe to support the transition to EVs. A quieter and more comfortable ride is another benefit of not having an internal combustion engine. To provide charging services to various bikes, cars, which will require the power electronic circuits to work with incredibly wide battery voltage ranges, is the obvious problem for EV chargers. Because of its benefits for the economy and the fight against global warming, the usage of EVs and plug-in hybrid EVs is growing daily. There are two types of EV battery chargers: onboard and offboard. The ability to charge a vehicle's battery from any power outlet is made feasible by on-board equipment while the ability to charge a vehicle's battery from a specific charger at a charging station is called offboard charger. The electric vehicle (EV) market is experiencing significant global growth, fueled by increasing consumer awareness, stringent environmental regulations, and continuous improvements in battery technology. In 2023, the market was estimated at USD 500.48 billion and is expected to reach approximately USD 1,891.08 billion by 2032, with a compound annual growth rate (CAGR) of 13.8%. Governments worldwide are offering subsidies, tax breaks, and incentives to encourage EV adoption while investing heavily in charging infrastructure. Furthermore, advancements such as solid-state batteries and lithium-sulfur designs offer the potential for greater energy density and faster charging speeds, addressing key consumer concerns about range and convenience. Wireless charging technology and high-power DC fast chargers are further enhancing the practicality of EVs.

One of the most transformative developments is Vehicle-to-Grid (V2G) integration, which enables bidirectional power flow between EVs and the grid. This technology allows electric vehicles (EVs) to serve as energy storage solutions, aiding in grid stabilization and offering users an opportunity to lower their charging costs. Furthermore, the integration of artificial intelligence (AI), the Internet of Things (IoT), and autonomous driving technologies is enhancing EV performance, making them more intelligent and efficient..

## 2) LITERATURE REVIEW

Onar, et al. (2008)[1]. This paper introduces a bidirectional DC-DC converter tailored for automotive fuel cell applications. The converter supports bidirectional power flow, enabling regenerative braking that recovers kinetic energy during deceleration and stores it in the energy storage system. It also improves overall system efficiency by allowing power exchange between the fuel cell stack and the battery or ultracapacitor. This setup reduces the dependence on the fuel cell during transient load demands, enhancing the vehicle's fuel efficiency. However, the study does not explore advanced control methods such as model predictive control or adaptive control.

Lukic et al. (2008) [2]. This paper offers an in-depth analysis of the progress and challenges in automotive power electronics and motor drives, highlighting key areas for improvement in electric and hybrid vehicles. It addresses various topics, including power converter designs, motor control strategies, and thermal management techniques, all of which are essential for boosting the performance and efficiency of these systems. The paper also examines the integration of power electronics with different automotive subsystems. However, it does not explore the role of emerging wide-bandgap semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), which could greatly enhance the efficiency, power density, and thermal performance of power converters and motor drives in automotive applications.

Wong et al. (2010) [3]. This paper details the design and analysis of a dual-stator permanent-magnet motor for electric vehicles (EVs), offering increased torque density. The proposed motor design focuses on minimizing torque ripple and enhancing reliability. However, the study does not provide an in-depth performance evaluation across different operating conditions.

Khaligh, Li et al. (2010) [4] It paper offers an extensive review of battery modeling and management techniques for electric vehicles (EVs), emphasizing current methods and future directions. It covers different battery modeling approaches, such as equivalent circuit models and electrochemical models, which are crucial for estimating key battery states like state-of-charge (SoC) and state-of-health (SoH). However, the paper does not address the use of machine learning algorithms, which are becoming more popular for precise battery state estimation because of their ability to analyze complex data patterns and enhance prediction accuracy.

Emadi et al. (2011) [5] This paper offers a thorough overview of electric motor drive systems, covering their principles, modeling methods, and control strategies. However, it does not thoroughly examine the specific challenges associated with high-speed motor drives, such as thermal management, vibration control, and rotor dynamics. These challenges are crucial for reaching higher rotational speeds (e.g., over 20,000 RPM) and necessitate advanced designs in motor components like rotors and stators, along with innovative cooling and balancing solutions to maintain reliability and efficiency.

Husain (2011) [6] This paper offers a solid introduction to the design of electric and hybrid vehicles, covering key aspects like powertrain configurations and energy storage systems. However, it overlooks advanced thermal management techniques, such as phase change materials (PCM) and liquid cooling systems, which are vital for keeping battery temperatures within optimal ranges and preventing overheating. These modern approaches are crucial for improving battery efficiency, extending its lifespan, and supporting high-performance capabilities in electric vehicles.

The review by Egbue et al. (2012) [7] highlights key barriers to EV adoption, such as high costs, limited charging infrastructure, and range anxiety. However, it lacks a detailed exploration of consumer perception, which is crucial for understanding the psychological and social factors influencing EV adoption. Research like surveys from AAA and Pew Research Center show that while environmental concerns and fuel savings motivate potential buyers, issues like battery replacement costs, cold weather impacts, and trust in advanced features like autopilot systems remain significant obstacles. A deeper assessment of these perceptions could help tailor strategies to overcome such barriers.

Larminie et al. (2012) [8] This paper offers an in-depth look at electric vehicle (EV) technology, covering essential topics such as power systems and drivetrain mechanics. However, it doesn't adequately address the cybersecurity and data privacy challenges that arise in connected EVs. As modern EVs increasingly connect to personal devices for remote control and data sharing, they become more vulnerable to threats like phishing, malware, and data breaches. These risks could jeopardize user safety, financial data, and vehicle functionality. To minimize these dangers, it's crucial to implement strong cybersecurity measures and ensure compliance with privacy regulations such as GDPR and CCPA.

Yilmaz et al (2013) [9] This paper provides a thorough overview of battery charger topologies, charging power levels, and the infrastructure required for plug-in electric and hybrid vehicles. However, it doesn’t explore the economic challenges associated with deploying EV charging infrastructure. These challenges include high upfront installation costs, ongoing operational expenses, and maintenance issues. Economic factors like fluctuating energy prices and the "chicken-or-egg" dilemma—where a lack of charging stations discourages EV adoption, and vice versa—are significant obstacles to expanding infrastructure. Additionally, public funding programs, such as the U.S. Bipartisan Infrastructure Law, aim to address these economic hurdles by supporting the development of large-scale EV charging networks to promote widespread adoption.

The paper by Rajashekara (2013) [10] examines propulsion system strategies for electric, hybrid, and fuel cell vehicles, covering aspects like energy efficiency and powertrain integration. However, it does not fully explore advanced sensing technologies, such as LiDAR, radar, and multi-sensor fusion systems, which are essential for enhancing vehicle safety, performance, and situational awareness. These technologies enable precise environmental perception, collision avoidance, and optimized energy management, playing a critical role in connected and autonomous EVs.

The review by Gao et al. (2016) [11] a detailed analysis of charging strategies for lithium-ion batteries in electric vehicles (EVs), with a focus on methods like constant current-constant voltage (CC-CV) and pulse charging. However, it doesn't consider the effects of extreme weather conditions, such as very cold or hot temperatures, which can greatly impact battery performance and charging efficiency. In cold weather, chemical reactions inside the battery slow down, leading to reduced range—up to 40%—and longer charging times. On the other hand, hot weather can accelerate battery degradation due to overheating, shortening the lifespan of the battery. Integrating thermal management techniques to address these challenges is essential for ensuring that EVs perform reliably in a variety of climates.

The paper by Cetin et al. (2016) [12] focuses on designing a high-efficiency phase-shifted full-bridge converter for on-board EV chargers, emphasizing operational efficiency and power density. However, it does not adequately address thermal management, which is critical for preventing overheating in high-power applications, especially with components like Insulated-Gate Bipolar Transistors (IGBTs). Additionally, the paper lacks a long-term reliability analysis, essential for evaluating the durability of components under continuous thermal and electrical stresses, which are common in EV charging systems operating in diverse environmental conditions.

The review by Peltoniemi et al. (2016) [13] explores the impact of electric vehicle (EV) charging standards on the development of smart grids, focusing on factors such as interoperability and grid integration. However, it does not fully address regulatory and policy challenges, such as the lack of consistent global charging standards and limited government incentives for infrastructure development. These issues pose significant barriers to the widespread adoption of EVs and smart grids, as fragmented policies can slow down standardization efforts and deter private investment in advanced charging networks, which are essential for supporting the transition to electrification.

The paper by Shafiei et al. (2016) [14] offers an in-depth review of electric vehicle (EV) charging technologies, covering different topologies and operational strategies. However, it does not consider the cybersecurity risks that are becoming increasingly important as EV charging systems rely more on interconnected networks. Vulnerabilities, such as unauthorized access, malware attacks, and compromised communication protocols, could disrupt charging services or expose user data. To address these concerns, it is essential to implement strong encryption, intrusion detection systems, and standardized cybersecurity protocols to ensure the safety and reliability of EV charging infrastructure.

The paper by Mouli, Bauer et al. (2016) [15] presents a system design for a solar-powered EV charging station at workplaces, focusing on optimizing the orientation of photovoltaic (PV) panels and assessing storage integration to minimize grid dependence. However, it does not adequately consider the effects of weather variability, such as lower solar insolation during cloudy or winter conditions, which can substantially impact energy production. To address these challenges, integrating strategies like dynamic energy forecasting models or hybrid systems that combine solar and wind energy could help maintain consistent charging availability, regardless of changing weather conditions.

The review by Alvarez-Alvarez et al. (2017) [16] paper offers a thorough examination of wireless power transfer (WPT) technology for electric vehicles (EVs), covering inductive and capacitive systems, standards, and safety factors. However, it does not provide a detailed analysis of dynamic wireless charging, which presents challenges such as maintaining efficient power transfer despite coil misalignment, handling fluctuating power demands while the vehicle is in motion, and ensuring smooth communication between the EV and charging infrastructure. Addressing these challenges is essential for enhancing the reliability and scalability of dynamic WPT systems in real-world applications.

The review by Husain et al. (2017) [17] is integration of renewable energy sources, such as solar and wind, into EV charging stations is discussed, with a focus on grid integration and energy management strategies. However, it does not provide a comprehensive analysis of the economic feasibility and scalability of these systems, which are influenced by factors like high initial installation costs, payback periods, and the varying renewable energy potential in different regions. Addressing these factors is essential for evaluating the long-term viability and ensuring the widespread adoption of renewable-powered EV charging infrastructure.

The paper by Hoffmann et al. (2018) [18] implementation of GaN-based phase-shifted full-bridge converters for EV battery chargers is examined, highlighting their high efficiency and compact design. However, the discussion does not sufficiently address cost-effectiveness and manufacturability, which are crucial for scaling GaN technologies. Key challenges include the higher cost of materials, complex fabrication processes, and the need to ensure reliable mass production while preserving performance advantages, such as reduced thermal dissipation and high power density.

The review by Deb et al. (2018) [19] provides a comprehensive overview of energy storage technologies for electric vehicles, including lithium-ion batteries and emerging alternatives. however, it does not evaluate the long-term performance of these technologies, which is essential for understanding degradation patterns, lifecycle costs, and reliability under different operational conditions. addressing these factors would be crucial to assess the sustainability and economic feasibility of energy storage systems in EV applications.

The review by Musavi, Edington, and Eberle (2019) [20] provides a thorough analysis of on-board charger topologies for plug-in hybrid electric vehicles (PHEVs), discussing various converter types and control methods. however, it does not include a comparative analysis of bidirectional on-board charger topologies for vehicle-to-grid (V2G) applications, which are essential for enabling energy flow back to the grid during peak demand. challenges like optimizing power flow, ensuring grid compatibility, and tackling hardware complexity in bidirectional systems need more in-depth exploration to effectively support V2G integration.

The paper by Iyer et al. (2020) [21] analyzes power delivery systems for extreme fast-charging (XFC) stations, focusing on converter topologies and system design. however, it does not consider emerging semiconductor technologies like wide bandgap materials such as SiC and GaN, which provide higher efficiency, reduced switching losses, and more compact designs. incorporating these technologies could help address challenges in thermal management, high-frequency operation, and scalability for XFC applications.

The review by Mahmood et al. (2021) [22] explores the impact of EV charging infrastructure on the power grid, emphasizing grid integration and energy management strategies. however, it does not examine the environmental effects of EV charging, including emissions from electricity generation based on the grid mix and land use associated with charging stations. research indicates that using renewable energy for charging can significantly cut greenhouse gas emissions, whereas reliance on fossil-fuel-based grids and battery production adds to the environmental footprint. considering these factors is essential for evaluating the overall sustainability of EV charging systems.

The review by Khan et al. (2021) [23] examines EV charging techniques and their impact on the power grid, covering technical aspects like grid integration and charging methods. However, it lacks a detailed analysis of the economic benefits and costs of different charging infrastructures, such as installation expenses, operational costs, and return on investment. Addressing these factors is crucial for evaluating the financial viability and scalability of public and private charging networks, especially in light of high upfront costs and varying utilization rates.

The paper by Sutar and Patil (2022) [24] analyzes multistage constant current charging methods for batteries with an emphasis on improving charging efficiency. however, it overlooks the role of varying battery chemistries—such as lithium-ion, lithium-metal, and solid-state—which significantly affect charging performance due to differences in energy density, thermal behavior, and degradation patterns. for example, studies indicate that additives like cesium nitrate can boost the performance of lithium-metal batteries by enhancing interphase stability and supporting faster charging while preserving cycle life. recognizing these distinctions is essential for developing chemistry-specific charging strategies.

The review by Lipu et al. (2022) [25] offers an in-depth examination of power electronics converter technologies used in EVs, exploring different topologies and their applications. however, it lacks an evaluation of next-generation semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN), which play a key role in enhancing converter efficiency by minimizing switching losses, operating at higher temperatures, and allowing for more compact system designs. these advanced semiconductors are crucial for enabling quicker charging, improving driving range, and reducing powertrain costs in contemporary EV platforms.

The paper by Vishnuram et al. (2023) [26] explores how EVs integrate with renewable energy sources, highlighting their importance in the shift toward cleaner energy. however, it offers limited insight into the policy frameworks and infrastructure investments needed to support widespread EV adoption. effective measures—such as zero-emission regulations, financial incentives, expanded charging infrastructure, and grid modernization—are vital to overcoming challenges like equitable access and seamless integration with renewable energy systems.

The paper by Sutar, Mhabadi, and Patil (2023) [27] proposes a compact and efficient EV charger design utilizing a quasi-Z-source-fed phase-shifted full-bridge converter, focusing on achieving reduced size and enhanced performance. however, it does not include experimental validation for high-power scenarios, which is crucial for evaluating the charger's reliability and thermal management at increased power outputs. conducting real-world tests would help reveal possible concerns such as thermal overload, electromagnetic interference, and mechanical stress on components during extended operation.

## 3) CHARGERS OF EV

### A. AC chargers

AC chargers play an essential role in the EV ecosystem by offering a more affordable and easily accessible option for charging, particularly suited for home and public locations where slower charging speeds are acceptable. Unlike DC fast chargers, which supply high-power DC directly to the battery, AC chargers depend on the vehicle's onboard charger to convert grid-supplied AC into DC for battery storage. The basic operation of an AC charger starts with drawing AC power from a standard electrical outlet, usually 120V or 240V based on regional standards. A rectifier circuit within the charger converts this AC into pulsating DC, which is then filtered using capacitors and regulated to maintain a consistent output suitable for charging. Modern AC chargers often include microcontrollers or a battery management system (BMS) that track real-time battery conditions—such as voltage, current, and temperature—and adjust the charging rate accordingly to enhance safety and efficiency.

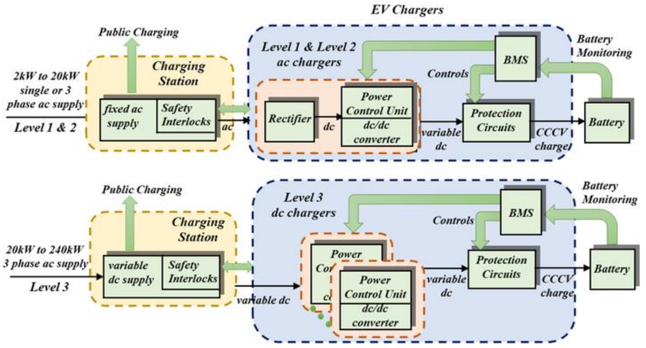

Figure 1. Level 1, 2 and 3 Charging systems

AC chargers are divided into Level 1 and Level 2 categories, depending on their power output. Level 1 chargers operate at 120V, delivering slower charging speeds, which makes them ideal for overnight home use. Level 2 chargers, operating at 240V, offer faster charging times, making them well-suited for residential garages or commercial locations. The benefits of AC chargers include their affordability, compatibility with standard electrical outlets, and ease of installation. However, they tend to offer slower charging speeds compared to DC fast chargers, limiting their suitability for quick top-ups during long trips. Despite this, AC chargers are a critical part of the EV infrastructure because of their accessibility and cost-effectiveness. As the global EV market expands, continued investment in AC charger technology will be essential for ensuring broad adoption, offering convenient and affordable charging solutions for everyday users.

### B. DC chargers

DC chargers are crucial devices that deliver direct current power straight to batteries, eliminating the need for onboard conversion systems. Unlike AC chargers, which rely on the vehicle's onboard charger to convert AC power into DC, DC chargers handle this conversion externally. This capability allows for quicker and more efficient charging, making them well-suited for applications like electric vehicles, renewable energy systems, and industrial environments where rapid energy restoration is required.

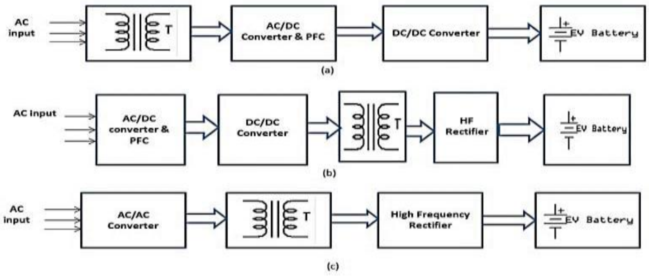

Figure 2. DC Charger configurations

The operation of DC chargers involves receiving AC power from the grid and converting it to DC using rectifiers and sophisticated power electronics built into the charger. This external conversion process allows DC chargers to bypass the restrictions of onboard systems, enabling them to deliver higher power directly to the battery. The charging process generally includes three phases. The first is the bulk charging phase, where the maximum current is provided to quickly charge the battery to about 80% of its capacity. Next is the absorption phase, where the current tapers off as the battery nears full charge, stabilizing the voltage and preventing overcharging. Lastly, the float phase maintains the battery at full charge, supplying a small maintenance current to keep it at 100% without affecting its longevity. DC chargers are commonly found in EV fast-charging stations due to their ability to deliver high power, ranging from 50 kW to 350 kW or more. This allows for much faster charging compared to AC chargers, enabling an EV battery to go from 20% to 80% in just 20–30 minutes, depending on the vehicle and charger specifications. Besides EVs, DC chargers are also used in renewable energy systems to store excess energy from solar or wind sources for later use. They are also employed in industrial applications like backup power systems and large-scale energy storage solutions.

The benefits of DC chargers include their speed and efficiency in delivering high power directly to batteries. They also integrate advanced communication protocols and safety features that ensure optimal performance while protecting against issues like overheating or overcharging. However, DC chargers are more expensive than AC chargers due to their intricate design and high-power components. Additionally, they require specialized infrastructure with high-capacity electrical connections, making them less practical for residential use.

## 4. POWER CONVERTERS IN CHARGERS

### A. AC/DC converters

### i. AC to DC Conversion (Rectification)

Rectification refers to the conversion of alternating current (AC) into direct current, a crucial process in power electronic systems, especially in power supplies and battery charging circuits. Rectifiers come in two main types: uncontrolled and controlled. Uncontrolled rectifiers use diodes to allow current to flow in only one direction. Half-wave rectifiers let only one half of the AC cycle pass, while full-wave rectifiers make use of both halves—either by employing a center-tapped transformer with two diodes or a full-bridge configuration with four diodes. Controlled rectifiers use thyristors or power transistors, which allow for adjusting the output voltage and current by modifying the firing angle of these devices. This makes them ideal for uses such as motor control, regulated power supplies, and intelligent battery charging systems.

### ii. AC to AC Conversion

AC to AC conversion involves changing one AC waveform into another with different voltage or frequency characteristics, without converting the signal to DC. One method of achieving this is through AC voltage controllers, which adjust the output voltage while keeping the frequency constant. These controllers typically use components like triacs or thyristors and are commonly used in applications such as controlling fan speeds, dimming lights, and regulating induction motors. Another technique is the cycloconverter, which directly converts a fixed-frequency AC input into a variable-frequency AC output. Cycloconverters are used in applications that require low output frequency and high torque, such as in industrial rolling mills. Matrix converters are an advanced type of AC-to-AC conversion. They employ an array of bidirectional switches to directly link input and output phases, providing compact and efficient conversion with control over both voltage and frequency, though they present design and control challenges.

### iii. AC to AC Conversion (Inversion)

Although the term "inversion" is typically associated with the conversion of DC to AC, in AC systems, it can also refer to situations where power flow is reversed, such as in regenerative braking or bidirectional energy transfer. These applications use regenerative converters or bidirectional AC-AC converters, which enable energy to flow back from the load to the source. This is commonly achieved through back-to-back converters, which combine a rectifier and an inverter, or through matrix converters that support reverse power flow. These technologies play a key role in applications like electric drives and smart grids, where effective energy recovery is critical.l.

### iv. Combined Conversions (AC–DC–AC)

AC–DC–AC conversion consists of two main stages: rectification followed by inversion. Initially, the AC input is converted to DC using either uncontrolled or controlled rectifiers. This DC is then converted back to AC through a DC-AC inverter. This configuration is especially useful in systems requiring adjustable frequency or voltage, such as variable frequency drives (VFDs) for motor control, uninterruptible power supplies (UPS), and renewable energy systems like wind or solar inverters. The benefit of this method is its versatility and control, enabling precise regulation of output voltage and frequency. Additionally, modern techniques such as Pulse Width Modulation (PWM) in the inverter stage ensure high-quality AC waveforms, with minimized harmonic distortion and enhanced system performance. These systems can also facilitate bidirectional energy flow, supporting applications like regenerative braking and energy feedback to the grid..

## B. DC/DC power converters

### i. Flyback Converters

AC–DC–AC conversion consists of two main stages: rectification followed by inversion. Initially, the AC input is converted to DC using either uncontrolled or controlled rectifiers. This DC is then converted back to AC through a DC-AC inverter. This configuration is especially useful in systems requiring adjustable frequency or voltage, such as variable frequency drives (VFDs) for motor control, uninterruptible power supplies (UPS), and renewable energy systems like wind or solar inverters. The benefit of this method is its versatility and control, enabling precise regulation of output voltage and frequency. Additionally, modern techniques such as Pulse Width Modulation (PWM) in the inverter stage ensure high-quality AC waveforms, with minimized harmonic distortion and enhanced system performance. These systems can also facilitate bidirectional energy flow, supporting applications like regenerative braking and energy feedback to the grid.

### ii. Buck Converters (Step-Down)

A buck converter is a non-isolated step-down converter that lowers the input voltage to a reduced output voltage while maintaining high efficiency. It works by rapidly switching a power transistor on and off. When the switch is on, energy flows from the input to the output via an inductor, charging the output capacitor. When the switch is off, the inductor continues to supply energy to the output, maintaining current flow. Due to its simplicity, compact design, and high efficiency, the buck converter is commonly used to power devices that require a stable, lower voltage than the input. Applications include CPU voltage regulation, battery-operated electronics, and LED drivers. With efficiency levels often exceeding 90% and continuous output current, buck converters are especially suitable for devices that are sensitive to load changes.

### iii. Boost Converters (Step-Up)

A boost converter is a non-isolated DC-DC converter that increases the input voltage to a higher output voltage. When the switch is closed, current flows through the inductor, storing energy in its magnetic field. When the switch opens, the magnetic field of the inductor collapses, releasing energy to the output via the diode, thereby boosting the voltage. Boost converters are typically used when the input voltage is lower than the required output voltage. Common applications include powering high-voltage circuits from low-voltage sources, such as in flashlights, electric vehicles, or solar power systems. Although boost converters are efficient at low to medium power levels, the output current tends to be pulsating, requiring proper filtering to minimize ripple.

### iv. Buck-Boost Converters

A buck-boost converter integrates the features of both buck and boost converters, allowing it to either increase or decrease the input voltage based on the duty cycle. This flexibility makes it especially useful in situations where the input voltage fluctuates above or below the required output voltage. The basic non-isolated design operates by switching an inductor in and out of the circuit to either store or release energy, adjusting the voltage level. A challenge with traditional buck-boost converters is that they invert the output voltage polarity relative to the input. However, modified designs like the SEPIC (Single-Ended Primary Inductor Converter) and Cuk converter can deliver non-inverted outputs. Buck-boost converters are particularly suited for battery-operated systems with varying voltage levels, such as in portable devices or renewable energy systems that face unpredictable input conditions.

### v. Dual Active Bridge (DAB) Topology

The DAB topology is a commonly used DC-DC converter design that facilitates efficient, high-frequency, and bidirectional power transfer. It is especially preferred in applications requiring galvanic isolation and bidirectional energy flow, such as battery energy storage systems, electric vehicle charging stations, and renewable energy systems like photovoltaic inverters and fuel cells. The DAB converter comprises two full-bridge circuits—one on the primary side and one on the secondary side—connected through a high-frequency transformer. Both bridges are actively controlled, in contrast to traditional unidirectional converters, where typically only one side is switched. This active control of both sides gives the DAB converter its distinctive ability to manage seamless bidirectional power flow. The phase shift between the square-wave voltages generated by the two full-bridges is the key control parameter. The power transfer’s magnitude and direction are directly influenced by this phase shift. When there is no phase difference, no power is transferred; altering the phase difference allows power to flow in either direction depending on which bridge leads. One of the main advantages of the DAB topology is its operation under Zero Voltage Switching (ZVS) conditions, applicable across both high and low loads. ZVS minimizes switching losses and reduces electromagnetic interference (EMI), improving the converter’s efficiency, particularly at higher frequencies. Additionally, the use of high-frequency transformers reduces the size of passive components, resulting in a more compact and lightweight design.

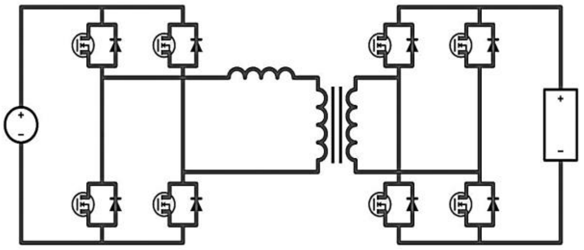

*Figure 3 . DAB Topology*

Source: GitHub, MathWorks MATLAB Central File Exchange

The DAB converter is inherently modular, making it easy to scale up in high-power systems. Its symmetric design facilitates the creation of distributed energy systems, where power can be transferred to or from different storage elements based on the system's needs. Additionally, the transformer's isolation ensures safety and adherence to grid standards in high-voltage applications. However, despite its many benefits, the DAB topology also comes with certain challenges. The complexity of control increases because of the need for synchronized and precise phase modulation between both bridges. Furthermore, the converter's efficiency can decrease under light-load conditions unless soft-switching is maintained across all operating points. Some advanced solutions tackle this issue through adaptive control techniques, variable frequency operation, or by incorporating auxiliary circuits..

### vi. Full-Bridge LLC Topology

The Full-Bridge LLC resonant converter is an advanced isolated DC-DC topology, renowned for its high efficiency and exceptional performance in medium- to high-power applications. It is commonly used in power supplies for servers, telecommunications, battery chargers, and electric vehicle systems, where minimizing losses and electromagnetic interference (EMI) is essential. The name of the topology comes from the resonant tank, which consists of two inductors (L1 and Lr) and a capacitor (Cr). This resonant tank shapes the system's resonant frequency and facilitates soft-switching conditions.

The LLC converter functions based on resonance, where energy oscillates between inductive and capacitive components. In each switching cycle, the energy stored in the resonant tank is transferred to the load through a high-frequency transformer that provides both isolation and voltage scaling. The converter is capable of achieving Zero Voltage Switching (ZVS) for the primary-side switches and Zero Current Switching (ZCS) for the secondary-side rectifiers. These soft-switching conditions significantly reduce switching losses and minimize component stress, enabling the converter to operate at higher switching frequencies with better thermal performance and lower EMI.

One of the key features of the Full-Bridge LLC topology is its ability to maintain high efficiency over a wide range of input voltages and load conditions. Unlike traditional hard-switched converters, which experience significant switching losses at light loads, the LLC converter maintains efficient operation due to its resonant nature. The full-bridge design, which uses four switches on the primary side, improves power handling capabilities compared to half-bridge converters, making it ideal for higher power applications..

Control of the LLC converter typically involves adjusting the switching frequency rather than the duty cycle. This frequency modulation method enables the converter to stay in resonance with the tank's natural frequency, ensuring Zero Voltage Switching (ZVS) under varying load conditions. However, the proper design of the resonant components, particularly the selection of inductors and capacitors, is critical to ensure that the gain and load regulation remain within acceptable limits. Incorrect design choices may lead to loss of resonance or suboptimal performance under specific operating conditions.

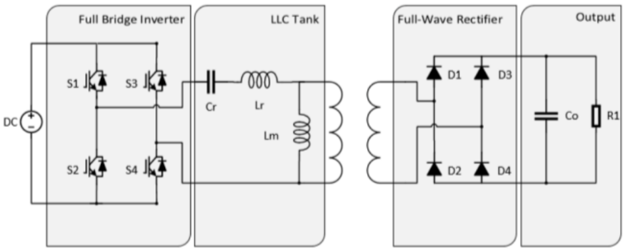

*Figure 4 . Full-Bridge LLC Topology*

**Source**: ResearchGate

In a Full-Bridge LLC converter, the primary side consists of a full-bridge inverter and an LLC resonant network that includes a resonant inductor, magnetizing inductance, and a capacitor. This section takes the DC input and generates a high-frequency AC signal. The signal then passes through a high-frequency transformer that provides voltage scaling and isolation. On the secondary side, the AC signal is converted back to DC using a full-wave rectifier, and an LC filter smooths the output before it is supplied to the load or battery.

The Full-Bridge LLC topology offers excellent load regulation and fast transient response, which are critical for dynamic applications such as battery charging. In these scenarios, it is vital to maintain stable voltage and current profiles during both charge and discharge cycles. Additionally, LLC converters are naturally more resistant to noise and harmonics due to their sinusoidal current waveform and reduced switching spikes. With the growing demand for compact and efficient power electronics, LLC converters are often paired with digital control systems such as the TI C2000 series microcontrollers. These controllers allow precise frequency control, real-time feedback monitoring, and protection features like over-voltage, over-current, and over-temperature safeguards. This integration of digital control improves system performance and reliability.

### vii. Phase-Shifted Full-Bridge (PSFB) Topology

The design of a PSFB converter-based battery charging system using MOSFETs revolves around achieving high efficiency, reliability, and adaptability for medium to high-power applications. This topology is particularly advantageous due to its ability to implement soft-switching techniques such as ZVS, which significantly reduces switching losses and enhances overall performance.

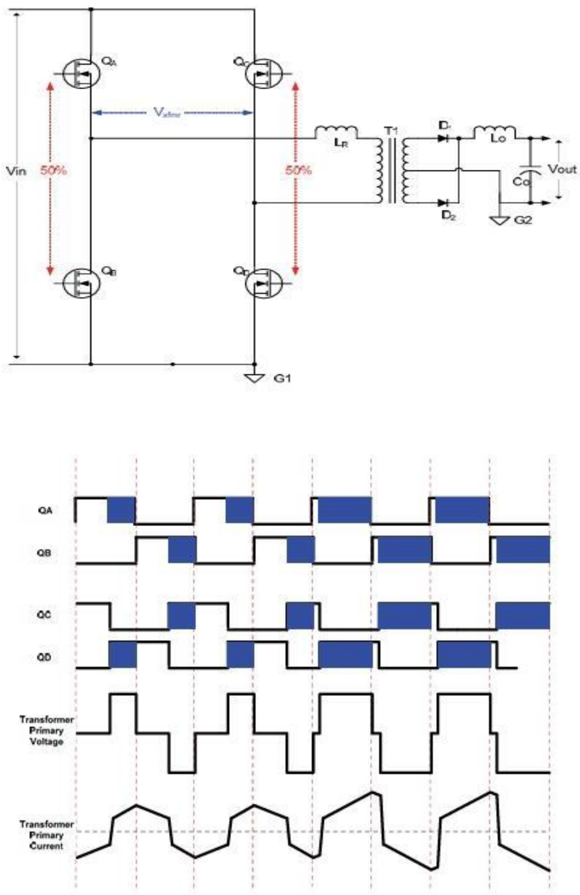

*Figure 5 PSFB Converter*

**Source** :- (Texas Instruments Incorporated, 2014)

The PSFB converter functions by phase-shifting the gate signals between the leading and lagging legs of an H-bridge configuration. The primary side of the converter uses MOSFETs arranged in this H-bridge layout, where they alternately switch the input DC voltage to AC, powering the transformer. During operation, diagonal switches (e.g., QA-QD and QB-QC) conduct at the same time, transferring energy to the transformer in their ON states. There are also intervals where either the top switches (QA-QB) or bottom switches (QC-QD) are ON simultaneously, creating a short circuit across the transformer's primary winding. This short circuit condition supports ZVS transitions by keeping circulating current through the transformer's leakage inductance. ZVS ensures that the MOSFETs turn ON when their drain-source voltage is zero, which reduces switching losses and minimizes electromagnetic interference.

On the secondary side, synchronous rectification is used with standard diodes. Synchronous rectifiers are preferred due to their lower conduction losses, which significantly enhance the system's efficiency, especially in high-power applications. The rectified DC output from the secondary is regulated to meet the specific needs of battery charging. The transformer plays a crucial role by providing galvanic isolation between the primary and secondary circuits, while also stepping down the voltage as needed. Its leakage inductance is intentionally leveraged as part of a resonant circuit to enable Zero Voltage Switching (ZVS). If additional inductance is necessary to achieve ZVS across a broader load range, external inductors can be added to supplement the transformer's inherent properties. When comparing the PSFB to the DAB topology, one of the main benefits is the simpler control design. While the DAB allows for bidirectional power transfer and is highly modular, it requires precise synchronization between two actively controlled full bridges, which increases the complexity and computational load of the control system. In contrast, the PSFB uses a single full bridge on the primary side and avoids the need for complex bidirectional phase modulation, making it easier to implement in unidirectional systems like battery chargers. When compared to the Full-Bridge LLC topology, PSFB converters offer superior load regulation and more flexible control. Although LLC converters are known for their high efficiency due to their resonant operation and soft-switching capability across a wide load range, they typically require variable frequency control. This introduces additional design challenges and necessitates careful selection of resonant components. PSFB, however, operates with a fixed switching frequency, which simplifies the design of magnetic components, filter tuning, and synchronization with digital control systems. Another benefit of the PSFB is its strong performance under dynamic and high-load conditions, which are common in battery charging applications. The topology is capable of handling high currents and power levels without compromising efficiency or response time. It also integrates well with digital control platforms, such as the C2000 series, enabling advanced features like adaptive phase control, digital regulation of current and voltage, and protection mechanisms such as overcurrent and undervoltage lockout. Additionally, PSFB provides improved scalability for varying power levels and load requirements, allowing for more efficient system designs in diverse applications. Its versatility and robustness make it an ideal choice for a wide range of power conversion tasks, especially in energy-intensive systems.

## 5) ELECTRIC VEHICLE FAST-CHARGING TECHNOLOGY AND SYSTEM

Electric vehicle charging systems are generally categorized into two main types: slow charging and fast charging. Level 1 and Level 2 onboard chargers are typically classified as slow charging systems. For example, Level 1 onboard chargers require approximately 8 to 10 hours to fully charge a power battery, with their output power typically limited to residential applications of less than 10 kW. On the other hand, Level 2 chargers charge the batteries at a faster rate, with power levels that can reach up to 20 kW, and are commonly found in public locations such as shopping malls. Currently, there are two common types of topologies used for slow charging systems, one of which is the single-stage configuration. This system includes a high-frequency DC/DC converter and an unregulated rectifier. The single-stage topology can feature various designs such as push-pull, half-bridge, full-bridge, flyback, or forward configurations. Its main advantage is its simple structure and fewer components, but it has the downside of potentially causing grid pollution due to its direct connection to the grid. Alternatively, a two-stage charging system is used, where a DC/DC converter is placed in the backstage and a power factor correction stage is implemented in the frontstage. This approach is more efficient in terms of managing grid power quality and offers better overall performance, though it involves a more complex design. The two-stage charging system can effectively address the issues of the low power factor and serious harmonic pollution but it has a high cost and low efficiency. Currently, the conventional PID control method is widely used for slow-charging systems but more advanced control methods, such as BP neural network PID control methods and fuzzy adaptive PID control methods, have also been developed, which can significantly affect the charging output characteristics. Consumer demand for quicker charging systems has grown along with the number of EVs in use because slow-charging systems offer poor power output and a lengthy charging period. Among the non-vehicle charging options are fast-charging systems, which can be categorized as either quick or ultra-fast. In the parts that follow, the off-board charging systems' structure and control approach are thoroughly explained.

Level 3 charging systems, often referred to as fast chargers, are capable of delivering high current levels—up to around 400 A. These systems typically operate within a power range of 50 kW to 350 kW and can fully charge an electric vehicle's battery in roughly 20 to 30 minutes. Taking this a step further, ultra-fast charging systems push the power level even higher, exceeding 400 kW, and are able to recharge a battery pack in close to 20 minutes or less. While fast charging technology has already seen significant development and widespread adoption, ultra-fast charging is emerging as a promising solution for reducing charging time even further, making it more practical for long-distance travel and high-demand scenarios. This trend suggests that ultra-fast charging systems could become more prevalent in the coming years as the demand for rapid energy replenishment grows. Further discussions in Section 3 of this paper explore the specific standards and interface protocols relevant to these high-speed charging technologies. Additionally, Table 1 provides a breakdown of the different charging types and levels, and emphasizes the capabilities of advanced fast and ultra-fast chargers that operate in the high hundreds of kilowatts range.

| **Charging Type (Battery Capacity) Criterion** | **Level 1** | **Level 2** | **Level 3 (Fast)** | **Ultra-Fast Charging** |
|---|---|---|---|---|
| **Charging Location** | On-board | On-board | Off-board | Off-board |
| **Voltage/V** | 120/230 | 208/240 | 300–600 | >800 |
| **Current/A Time** | 12–16 | 15–80 | ≤400 | >400 |
| **Power/kW** | 1.44–1.92 | 3.1–19.2 | 50–350 | ≥400 |
| **Charging Time**<br>**(Battery Capacity)** | 11–36 h (16–50 kWh) | 2–6 h (16–30 kWh) | 30 min (20–50 kWh) | 10 min (20–50 kWh) |

Table 1. Charging levels

## 6) CONTROLLER DESIGN

The integration of the C2000 microcontroller into the design and control of a Phase-Shift Full Bridge converter-based battery charging system provides a highly efficient and intelligent platform for managing power flow. Developed by Texas Instruments, the C2000 family is engineered specifically for real-time control in power electronics, making it a strong fit for the demands of digitally controlled DC-DC converters such as the PSFB. These microcontrollers are equipped with key features including high-resolution Pulse Width Modulation (PWM) modules, fast and precise Analog-to-Digital Converters (ADCs), and a powerful Digital Signal Processing (DSP) core. These elements work together to allow for accurate switching control, fast feedback loop response, and real-time execution of complex control algorithms, such as phase-shift modulation and ZVS—essential for reducing switching losses and improving efficiency. In a PSFB converter, the C2000 controls the phase shift between the bridge legs, which determines the effective duty cycle and regulates output power. By monitoring real-time data such as input/output voltage and current, the controller dynamically adjusts the phase angle to ensure the battery receives stable and optimal charging power, even under varying conditions. The ADCs provide rapid sampling of system parameters, while the PWM modules generate finely-tuned gate signals for the power switches.

Additionally, the C2000 supports multiple communication protocols (SPI, UART, CAN, I2C), enabling smooth communication with other subsystems like the Battery Management System (BMS) and user interface modules. This integration allows for coordinated control, system diagnostics, safety monitoring, and user configurability. Furthermore, the microcontroller facilitates advanced features like adaptive control, fault detection, and thermal management, enhancing system robustness. It also supports digital compensation techniques (such as PID control or model predictive control) to ensure high performance across a wide range of input conditions and load profiles.

### A. Component Selection

MOSFETs are exclusively used in this design due to their superior switching characteristics compared to other semiconductor devices like IGBTs or BJTs. Their fast-switching speeds enable operation at high frequencies (typically 100–150 kHz), while their low conduction losses reduce heat generation during operation. Additionally, robust body diodes in MOSFETs support ZVS operation effectively. The transformer used in this system is designed with optimized leakage inductance to facilitate resonant transitions required for ZVS operation. If necessary, external inductors can be added to improve performance across varying load conditions.

Parasitic output capacitances of MOSFETs are utilized as part of the resonant circuit, reducing component count while enabling soft switching.

### B. Efficiency Optimization

Efficiency optimization is a key aspect of PSFB converter design. Adjusting switching frequency based on load conditions ensures optimal efficiency across different operating ranges. Lower frequencies are used at light loads to maintain ZVS operation, while higher frequencies maximize power transfer under heavy loads. Maintaining ZVS at low loads can be challenging due to reduced circulating currents. Strategies such as increasing leakage inductance or using auxiliary circuits can help sustain resonant transitions under these conditions.

### C. Voltage Equalization

Voltage equalization in battery charging systems is essential to ensure uniform voltage distribution across all battery cells, preventing overcharging or undercharging that can lead to reduced battery lifespan and safety risks. Integrating temperature sensors into the equalization process enhances the system's ability to monitor and regulate charging conditions, particularly for batteries prone to thermal instability during operation.

## 7) CONCLUSION

In conclusion, this paper has explored the advancements and innovations in charging systems, highlighting their significance in modern technology. The evolution of charging systems has been driven by the need for efficiency, sustainability, and convenience. Key findings from this study include [list specific findings, e.g., improved charging speeds, enhanced energy efficiency, or innovative charging technologies. The implications of these developments are substantial, as they contribute to a more sustainable energy future by supporting the widespread adoption of electric vehicles and renewable energy sources. Furthermore, the integration of advanced charging systems into existing infrastructure presents opportunities for economic growth and environmental benefits. Future research should focus on addressing the challenges associated with scalability, cost-effectiveness, and user accessibility to ensure that these technologies reach their full potential. By continuing to innovate and improve charging systems, we can accelerate the transition to cleaner energy solutions and create a more sustainable future for generations to come.

## 8) REFERENCES

1. Onar, O. C., Miller, J. M., & Ozpineci, B. (2008). A bidirectional DC–DC converter for automotive fuel cell applications. *IEEE Transactions on Power Electronics, 23*(4), 2105-2113.

2. Lukic, S. M., Sun, P., & Emadi, A. (2008). Automotive power electronics and motor drives: Advances and challenges. *IEEE Transactions on Industrial Electronics, 55*(6), 2283-2301.

3. Wong, Y. K., Chau, K. T., Gao, F., Liu, C., & Qingxin, L. I. (2010). Design and analysis of a dual-stator permanent-magnet motor for electric vehicles. *IEEE Transactions on Industrial Electronics, 57*(4), 1459-1467.

4. Khaligh, A., Li, Z., & Emadi, A. (2010). Battery modeling and management of electric vehicle applications: State of the art and future trends. *IEEE Transactions on Vehicular Technology, 59*(9), 4261-4276.

5. Emadi, A., Williamson, S. S., & Khaligh, A. (2011). *Electric motor drives: Principles, modeling, and control.* John Wiley & Sons.

6. Husain, I. (2011). *Electric and hybrid vehicles: Design fundamentals.* CRC press.

7. Egbue, O., & Long, S. (2012). Barriers to widespread adoption of electric vehicles: A review. *Renewable and Sustainable Energy Reviews, 16*(7), 5445-5456.

8. Larminie, J., & Lowry, J. (2012). *Electric vehicle technology explained.* John Wiley & Sons.

9. Yilmaz, M., & Krein, P. T. (2013). Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles. *IEEE Transactions on Power Electronics, 28*(5), 2151-2169.

10. Rajashekara, K. (2013). Propulsion system strategies for electric, hybrid, and fuel cell vehicles. *IEEE Transactions on Industrial Electronics, 60*(1), 3-12.

11. Gao, Z., Lin, Y., & Hu, X. (2016). A review of charging strategies for lithium-ion batteries in electric vehicles. *Journal of Power Sources, 336*, 117-134.

12. Cetin, S., & Astepe, A. (2016). High-efficiency design for a phase-shifted full-bridge converter in on-board EV chargers. *IEEE Transactions on Power Electronics.*

13. Peltoniemi, P., & Kukkola, J. (2016). A review of electric vehicle charging standards and their impact on smart grid development. *Renewable and Sustainable Energy Reviews, 57*, 140-152.

14. Shafiei, S., Williamson, S. S., & Butt, M. M. (2016). Comprehensive review of electric vehicle charging technologies. *IET Electric Power Applications, 10*(7), 537-554.

15. Mouli, G. R., Bauer, P., & Zeman, M. (2016). System design for a solar-powered electric vehicle charging station for workplaces. *Applied Energy, 168*, 434-443.

16. Alvarez-Alvarez, M., Lopez, G., Gonzalez-Diaz, V., & Lorenzo, P. (2017). Review of Wireless Power Transfer Technology for Electric Vehicles. *Electronics, 6*(4), 83.

17. Husain, M. M., Tariq, M., Iqbal, A., & Rahman, M. K. (2017). Review on integration of renewable energy sources into electric vehicle charging stations. *Journal of Energy Storage, 26*, 100991.

18. Hoffmann, F., Prasobhu, P. K., Liserre, M., & Buticchi, G. (2018). Challenges in implementing GaN-based phase-shifted full-bridge converters for EV battery chargers. *IEEE Transactions on Power Electronics.*

19. Deb, S., Tammi, K., Mahmud, A., & Salo, J. (2018). Review of energy storage technologies for electric vehicles. *IEEE Transactions on Industry Applications, 54*(5), 4144-4156.

20. Musavi, F., Edington, M., & Eberle, W. (2019). A comprehensive review of on-board charger topologies for plug-in hybrid electric vehicles. *IEEE Transactions on Vehicular Technology, 68*(1), 14-30.

21. Iyer, V. M., Gulur, S., Gohil, G., & Bhattacharya, S. (2020). Power delivery system for extreme fast-charging (XFC) stations. *IEEE Transactions on Power Electronics.*

22. Mahmood, F., Khan, I., Iqbal, J., & Hasan, A. (2021). A comprehensive review on electric vehicle charging infrastructure and its impact on power grid. *International Journal of Energy Research, 45*(12), 17295-17318.

23. Khan, W., Ahmad, A., Alam, A., & Zafar, M. (2021). A review on electric vehicle charging techniques and its impact on the grid. *Archives of Electrical Engineering, 70*(1), 3-20.

24. Sutar, A. R., & Patil, M. S. (2022). Analysis of battery charging characteristics and a multistage constant current charging approach.

25. Sutar, A. R., Mhabadi, S. H., & Patil, M. S. (2023). A lightweight and efficient EV charger is designed using a quasi-Z-source-fed phase-shifted full-bridge converter.