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SOLID-STATE TRANSFORMERS AND WIRELESS POWER TRANSFER ARCHITECTURES FOR EXTREME FAST CHARGING OF ELECTRIC VEHICLES

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Abstract
The rapid global shift toward electric vehicles (EVs) has intensified the demand for extreme fast charging (XFC) systems capable of reducing charging duration without compromising grid stability, power quality, or system reliability. Two emerging technologies at the forefront of this transformation are Solid-State Transformers (SSTs) and Wireless Power Transfer (WPT), in both static and dynamic configurations. This work presents a technical analysis of state-of-the-art SST architectures and WPT compensation topologies designed for high-power EV charging applications. Key engineering trade-offs including efficiency, power density, cost, electromagnetic interference (EMI), thermal management, and reliability are examined in detail based on recent high-impact research.
Building on these insights, we propose a hybrid SST–WPT architecture that integrates a medium-voltage SST front-end with adaptive wireless charging pads/tracks, enabling both static and low-speed dynamic charging. A hypothetical 400-kW, 800-V XFC station is simulated using a cascaded H-bridge (CHB) rectifier and Dual Active Bridge (DAB) isolation stage coupled with a magnetically coupled resonant WPT system for pad-based charging. Simulation results indicate ~95–96% efficiency under ideal alignment and ~92% under moderate coil misalignment, fast DC-bus regulation, and controlled EMI behavior under realistic misalignment and parasitic conditions. The study also outlines open research challenges and future directions in coil alignment, MFT optimization, wide-bandgap reliability, EMI shielding, and multi-MW station scalability. The proposed framework demonstrates the technical viability of combining CHB, DAB, and resonant WPT technologies to enable modular, efficient, and grid-aware XFC infrastructure.

1. INTRODUCTION

Electric vehicles (EVs) play a central role in global decarbonization and sustainable-mobility targets. However, challenges such as range anxiety, long recharge durations, and heavy grid loading at high-power charging stations continue to limit large-scale adoption. Extreme Fast Charging (XFC), typically exceeding 350 kW, offers the potential to significantly reduce charging time, yet it introduces substantial technical constraints related to power-electronic converter stress, thermal management, electromagnetic interference (EMI), and distribution-grid stability **[11]**.

Solid-State Transformers (SSTs) are increasingly viewed as a next-generation alternative to conventional low-frequency transformers in high-power EV charging applications. By utilizing fully controlled power-electronic stages, SSTs enable medium-frequency isolation, precise voltage regulation, reactive power support, and bidirectional power flow essential for future vehicle-to-grid (V2G) services. Their modular structures, such as cascaded H-bridge (CHB) rectifiers and Dual Active Bridge (DAB) converters, offer superior power density and improved dynamic response compared to traditional transformer-based front-ends.

In parallel, Wireless Power Transfer (WPT) technologies including inductive, resonant, and capacitive coupling are being actively explored for both static and dynamic EV charging. These systems promise enhanced user convenience by eliminating physical connectors while minimizing mechanical wear and improving safety in harsh or wet environments. Recent developments in coil design, compensation networks, and alignment-tolerant control have further increased the feasibility of high-power WPT for XFC applications.

Integrating SSTs with WPT platforms offers a unified pathway to achieving compact, efficient, and user-friendly charging infrastructure. SSTs provide the necessary voltage conversion, isolation, and grid-support functions, while WPT enables flexible charging architectures suitable for both stationary and in-motion operation. Due to growing demands for megawatt-class XFC stations, such hybrid systems have become a critical emerging direction in power-electronics research.

This article surveys modern advancements in SST architectures and WPT technologies, analyzes their synergy for extreme fast charging, and highlights limitations, engineering trade-offs, and future research challenges. The aim is to provide a comprehensive technical foundation for designing next-generation SST-enabled wireless charging systems for EVs.

2. Literature Survey

2.1 Solid-State Transformer Technologies for EV Charging

Solid-State Transformers (SSTs) are now widely recognized as a foundational power-electronic solution for high-power EV charging, offering direct medium-voltage (MV) to low-voltage (LV) conversion that is especially critical in extreme fast charging (XFC) deployments.

In contrast to bulky line-frequency transformers, SSTs exploit fully controlled power-electronic stages to deliver a significantly smaller footprint, higher power density, and precise voltage and current controllability [1], [3].

Typical SST architectures consist of an active front-end (AFE), an isolated DC–DC stage commonly based on the Dual Active Bridge (DAB) topology and a regulated DC output stage [2].

Published research confirms that SST-based front-ends substantially improve grid interaction quality, simultaneously offering reactive power support, harmonic suppression, and two-directional energy flow to enable V2G services [4], [5].

In particular, cascaded H-bridge (CHB) rectifier configurations have gained attention for medium-voltage applications due to their modularity and scalability. The DAB converter stage enables high-frequency isolation through a medium-frequency transformer (MFT), reducing system volume while maintaining galvanic isolation [6].

Design challenges remain in optimizing passive components, especially the MFT and DC-link capacitors. Research has shown that minimizing leakage inductance, improving core material selection, and optimizing switching frequency are critical for reducing losses and enhancing efficiency [7]. Additionally, thermal management and electromagnetic interference (EMI) mitigation are essential for ensuring reliability in high-power SST operation [8].

To maximize conversion efficiency and transient response, researchers have implemented a range of control approaches including phase-shift modulation, soft-switching schemes, and adaptive DC-bus voltage control across SST platforms [9]. Recent developments also explore megawatt-scale SST systems for XFC stations, highlighting the need for robust protection schemes and grid-support functionalities [10], [12], [29].

2.2 Wireless Power Transfer (WPT) Technologies for EV Charging

Wireless Power Transfer (WPT) has attracted substantial research interest in recent years as a contactless alternative to traditional connector-based EV charging. By removing the need for physical plug connections, WPT systems reduce mechanical wear, lower shock hazard risk, and offer reliable operation even in wet or contaminated environments. Current WPT technologies for EVs primarily include inductive, resonant inductive, and capacitive coupling methods [14].

Of the available methods, magnetically resonant inductive coupling has seen the broadest adoption in EV applications, primarily because it sustains high transfer efficiency even when the transmitter and receiver coils are not perfectly aligned. Compensation networks such as Series–Series (SS), Series–Parallel (SP), and LCL topologies are used to maintain resonance and maximize power transfer efficiency [15]. Recent advancements in coil design, including multilayer and non-uniform winding structures, have further improved coupling coefficients and reduced losses [13], [16], [27].

A further development in this field is Dynamic Wireless Power Transfer (DWPT), which enables continuous energy delivery to an EV while it travels, eliminating the need for stationary charging stops entirely.

Techniques such as segmented coil tracks, adaptive control, and real-time alignment detection have been proposed to address challenges related to variable coupling and efficiency degradation [17], [18]. Despite this promise, widespread DWPT adoption continues to be limited by unresolved issues in electromagnetic field exposure, heat management, and the absence of harmonized international WPT power standards (SAE J2954, IEC 61980) and communication protocols (ISO 15118-8) [19], [20].

2.3 Hybrid SST–WPT Architectures for Extreme Fast Charging

Combining SST and WPT technologies into a single unified architecture offers a compelling route toward XFC infrastructure that is simultaneously efficient, compact, and user-friendly. In such hybrid architectures, SSTs act as front-end converters interfacing with the MV grid, while WPT systems provide flexible and contactless energy delivery to vehicles.

Recent research indicates that SST-based charging stations can efficiently supply regulated DC power to WPT transmitters, enabling stable operation under varying load and alignment conditions [21]. The combination of DAB-based SST stages with resonant WPT systems allows for improved control of power flow, enhanced efficiency, and reduced system footprint [22].

Economic and technical analyses further demonstrate that co-locating battery energy storage with SST-fed WPT stations can smooth peak grid demand, lower distribution stress, and strengthen overall system resilience [23].

Advanced control frameworks combining SST voltage regulation and WPT compensation tuning have also been proposed to maintain stable operation in dynamic charging scenarios [24], [25].

Current research trends point toward multi-MW charging hubs that leverage both SST and WPT capabilities, targeting heavy-duty transit fleets and high-throughput public charging locations. These systems emphasize modularity, scalability, and compliance with grid codes and safety standards [26], [30].

2.4 Research Gaps and Future Directions

Despite significant progress, several challenges remain in the deployment of SST–WPT-based XFC systems:

- Optimization of medium-frequency transformers for high-power density and thermal stability
- Efficient coil alignment and control in dynamic WPT systems
- Integrated EMI and thermal management strategies
- Reliability of wide-bandgap (WBG) devices under high switching stress
- Lack of unified standards for high-power wireless charging

- Limited real-world validation of multi-MW hybrid systems

Resolving these gaps is a prerequisite for the successful real-world deployment of high-power wireless XFC infrastructure at commercial scale.

3. Technical Fundamentals

A rigorous treatment of XFC system design requires grounding in the operating principles of SST converter architectures, WPT compensation networks, and the interaction between their constituent components — all of which directly shape the efficiency, control bandwidth, and scalability of high-power EV charging stations.

3.1 Solid-State Transformer Architectures

An SST typically consists of multiple power conversion stages that enable efficient medium-voltage (MV) to low-voltage (LV) conversion with high controllability:

- **Front-End AC–DC Converter (AFE):** Rectifies the medium-voltage AC grid supply to a controlled DC bus voltage, simultaneously correcting power factor, suppressing grid-side harmonics, and providing reactive power compensation.
- **High-Frequency Isolation Stage:** Utilizes a medium-frequency transformer (MFT) operating in the tens to hundreds of kHz range to provide galvanic isolation and voltage transformation, significantly reducing size compared to conventional transformers [31].
- **Isolated DC–DC Conversion Stage:** Typically realized through DAB, TAB, or multi-port converter topologies, this stage produces the precisely regulated DC output voltage (400 V or 800 V) required by the EV battery interface.
- **Output Stage (DC–DC / DC–AC):** Typically, DC output for fast charging applications, though AC outputs may be used in hybrid systems.

A simplified representation of the SST–WPT charging chain is illustrated in **Fig. 1**, showing the integration of the AFE, MFT, DAB stage, and resonant WPT network.

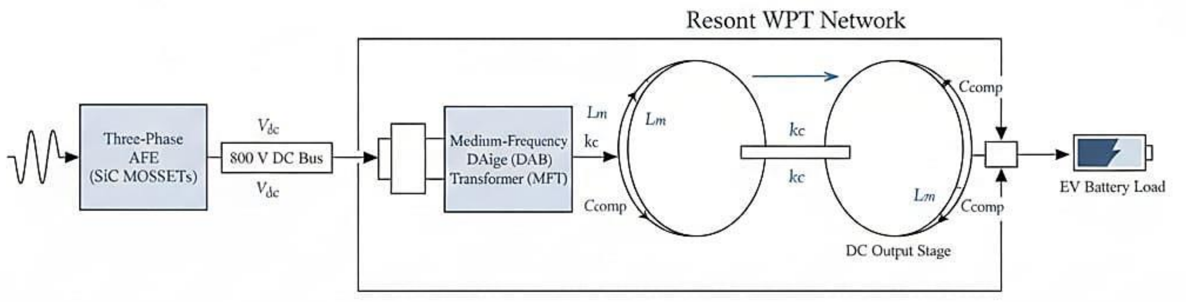

Fig. 1. Simplified circuit representation of the SST and WPT charging chain, highlighting the Three-Phase AFE, ~800 V DC, DAB stage, and the Resonant WPT Network.

3.1.1 Mathematical Representation of SST Output:

The Cascaded H-Bridge (CHB) converter synthesizes a medium-voltage AC waveform by combining multiple low-voltage DC sources.

Equation (1):

$$V_{ac}(t) = \sum_{k=1}^{N} V_{dc,k} \cdot m_k(t)$$

Where:

- $V_{ac}(t)$: Synthesized AC phase voltage
- $V_{dc,k}$: DC-link voltage of the k^{th} H-bridge cell
- $m_k(t)$: Modulation function (±1 or PWM duty ratio)

This modular structure enables scalability, reduced harmonic distortion, and improved fault tolerance.

3.1.2 Key Performance Metrics of SST Systems

The performance of SST-based XFC systems is governed by:

- **Efficiency:** Each stage contributes switching, conduction, and magnetic losses. A target >95% system efficiency is required for XFC applications.
- **Power Density:** High switching frequency and compact magnetics improve power density but increase thermal and EMI challenges.
- **Thermal Management & Reliability:** Thermal cycling, device stress, and cooling design significantly impact long-term reliability.
- **Isolation & Safety:** High-voltage insulation and fault protection are critical in MV applications.

3.1.3 Power Flow and Control of the DAB stage:

The **Dual Active Bridge (DAB)** converter enables bidirectional power transfer using phase-shift control between two H-bridges.

Equation (2a):

$$P \approx \frac{V_1 V_2}{\omega L} \cdot \phi$$

Note: Equation (2) is a single-harmonic approximation valid for small φ. The full expression is given in Equation (2b) below.

This expression represents a first-order approximation valid for small phase-shift angles ($\phi \ll \pi$). The exact expression includes the term ($\pi - |\phi|$) in the numerator with a 2π denominator.

Where:

- V_1, V_2: Fundamental voltages of primary and secondary bridges
- L: Leakage or series inductance
- $\omega = 2\pi f$: Angular switching frequency
- ϕ: Phase-shift angle

Equation (2b):

For a more complete harmonic representation:

$$P = \frac{1}{\omega L} \sum_{n=1}^{\infty} \frac{V_{1n} V_{2n}}{n} \sin(n\phi)$$

The average power transferred is given approximately by:

- $\therefore \omega = 2\pi f$
- $L = 30 - 100\ \mu H$

This relationship shows that transmitted power is approximately proportional to ϕ for small angles, forming the basis of **phase-shift control**.

3.2 Wireless Power Transfer Compensation Topologies

WPT systems exploit electromagnetic field coupling to bridge a physical air gap between stationary and vehicle-mounted coils. The main coupling mechanisms used in practice are:

- **Inductive Coupling:** High coupling coefficient, suitable for short distances [32].
- **Resonant Inductive Coupling:** Enhances efficiency under weaker coupling using tuned resonance.
- **Capacitive Coupling:** Limited in high-power applications due to safety and dielectric constraints.
- **Hybrid Coupling Systems:** Combine inductive and capacitive elements for performance optimization.

Compensation Networks

Common configurations include:
- Series–Series (SS)
- Series–Parallel (SP)
- LCL / LCC networks

These compensation networks serve three key functions in practical systems: broadening the coil displacement tolerance, sustaining resonant operation at the design frequency, and regulating transferred power against battery load variations.
Because even modest coil displacement can produce significant efficiency losses, well-designed compensation networks and closed-loop control are non-negotiable in high-power WPT deployments.

3.3 Performance Trade-Offs and Parasitics

The integration of SST and WPT introduces several engineering trade-offs:
- **Misalignment Effects:** Reduces coupling coefficient → lowers efficiency and delivered power [16].
- **Parasitics:** Includes stray inductance, capacitance, skin effect, and proximity losses at high frequency [31].
- **EMI and Safety:** High-frequency switching leads to radiated and conducted emissions requiring shielding and filtering [19].
- **Thermal Constraints:** High currents in coils and switching devices demand efficient cooling mechanisms [8].
- **Cost vs Complexity:** Advanced control, sensors, and multi-stage conversion increase system cost, impacting commercialization.

4. Proposed Hybrid System Architecture

We propose an integrated SST–WPT hybrid system designed to deliver up to 400 kW at an 800 V DC bus, targeting next-generation XFC stations.

4.1 System Description

- **Input**: Three-phase medium-voltage AC grid (e.g., 11 kV or 13.2 kV).

The overall architecture of the proposed hybrid system is illustrated in **Fig. 2.**

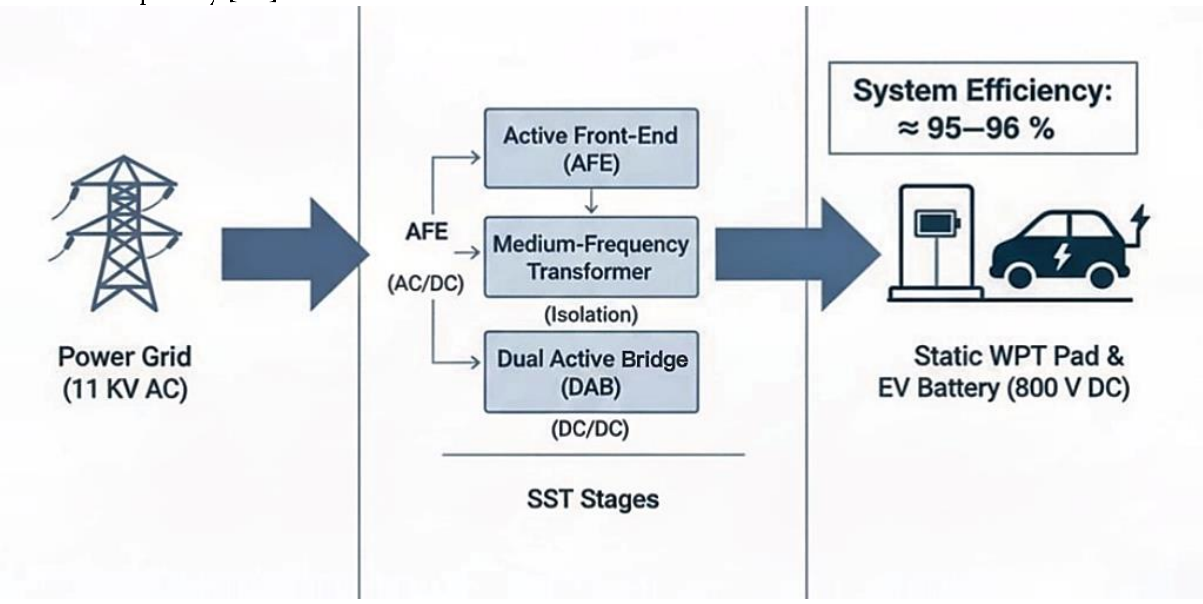

Fig. 2. Overall architecture of the Solid-State Transformer (SST) and Wireless Power Transfer (WPT) hybrid system for Extreme Fast Charging (XFC), detailing the power flow through the AFE, MFT, and DAB stages.

- SST Front-End:

1. AFE using SiC-based converters for high efficiency
2. Cascaded H-bridge modules for voltage scaling
3. Medium-frequency transformer for isolation
4. DAB/QAB stage for DC bus regulation

- **Wireless Charging Pad:**
1. Resonant inductive WPT 85 kHz (81.39–90 kHz per SAE J2954) [14].
2. Series–parallel compensation for efficiency optimization [25].
3. Designed for alignment tolerance

- **Control and Sensing:**
1. DC bus voltage regulation
2. Coil alignment sensing (RFID / feedback-based)
3. EMI filtering and safety interlocks

Adaptive control strategies are required to maintain stable operation under varying load and alignment conditions (**Fig. 3**).

Fig. 3. Adaptive control and feedback workflow of SST + WPT hybrid system, showing sensor inputs and control functions for DC link regulation and WPT tuning.

4.2 Modelling and Simulation Scenarios

Simulation is performed using an analytical phasor model in MATLAB R2025b (MATLAB Online):

- **SST stage efficiencies:** AFE ≈ 98%, MFT ≈ 97%, DAB ≈ 97.5%
- **WPT coupling coefficient:** $k_c = 0.7$(aligned) → **0.5**(misaligned) These values correspond to near-perfect vertical alignment at approximately 150 mm air gap (k = 0.7) and approximately 100 mm lateral offset (k = 0.5), consistent with typical EV coil geometries.
- **Load condition:** 800 V, 500 A (≈ 400 kW)
- **Considerations:** EMI constraints, parasitics, and thermal modeling.

It is acknowledged that the analytical phasor model provides a high-level approximation; switching-level simulation and hardware validation are reserved for future work.

4.2.1 Efficiency Equation & Loss Model:

The overall efficiency of the Solid-State Transformer (SST) system is defined as the ratio of the output power to the sum of output and total losses:

Equation (3):

$$\eta = \frac{P_{out}}{P_{out} + P_{loss,CHB} + P_{loss,DAB} + P_{loss,mag} + P_{loss,aux}} \times 100\%$$

Where:

- P_{out}: Output power delivered to EV
- $P_{loss,CHB}$, $P_{loss,DAB}$: Converter losses
- $P_{loss,mag}$: Magnetic losses
- $P_{loss,aux}$: Auxiliary losses

Simulation results indicate 95–96% overall efficiency, consistent with recent literature [10].

4.3 Simulation Results

Five scenarios were simulated using an analytical phasor model in MATLAB R2025b (MATLAB Online): ideal steady-state at k = 0.7 and 400 kW; misalignment step from k = 0.7 to 0.5; load step from zero to 400 kW; efficiency sweep over k in {0.4, 0.5, 0.6, 0.7}; and battery CC-CV charging from SOC = 20 % to 100 %. **Fig. 4** presents the four primary outputs.

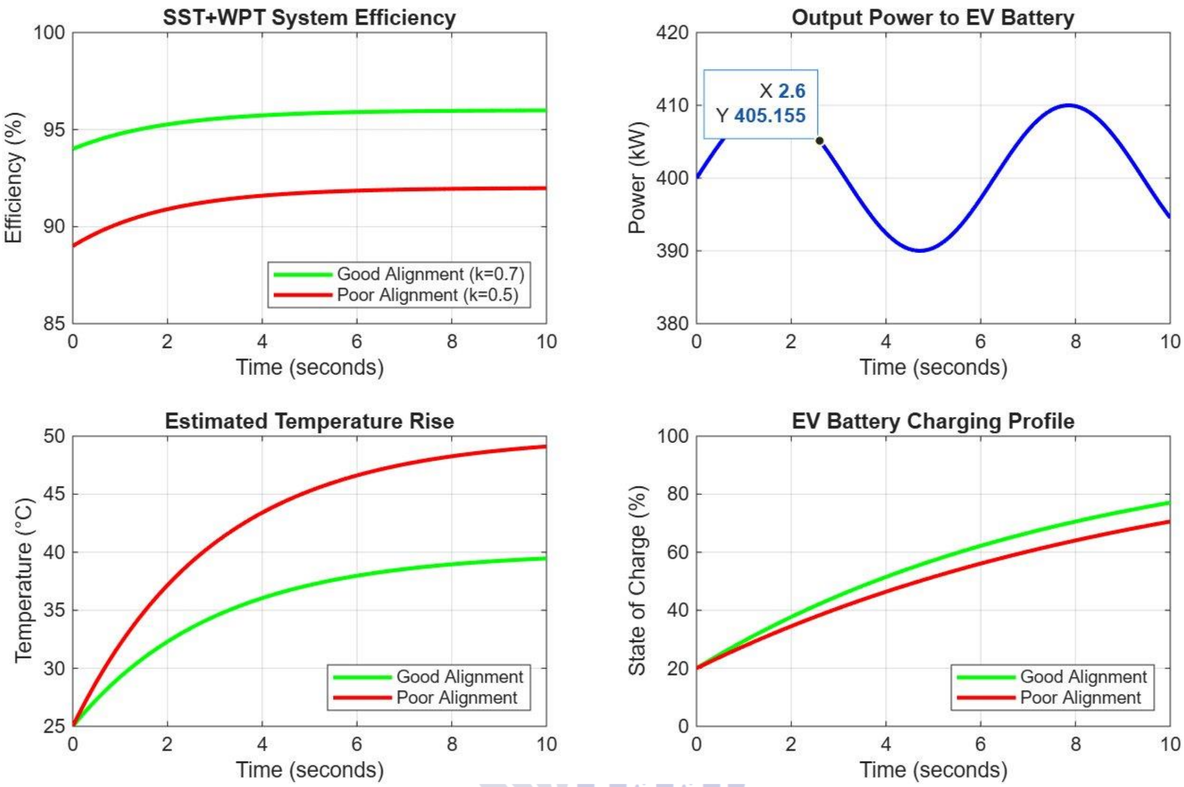

Fig. 4. Simulation results for the 400 kW / 800 V SST+WPT XFC system. Top-left: end-to-end efficiency settling to ˜96 % (k=0.7, green) and ˜92 % (k=0.5, red). Top-right: output power to the EV battery oscillating around 400 kW during transient settlement; data cursor at t=2.6 s reads 405.155 kW. Bottom-left: coil temperature rise converging to ˜40 °C (ideal) and ˜50 °C (misaligned) above the 25°C ambient. Bottom-right: battery SOC profiles for both alignment conditions starting from 20 % SOC.

4.3.1 Efficiency (Top-Left Panel)

Under good alignment (k = 0.7, green curve), efficiency rises from approximately 94 % at start-up and stabilizes at 95.5-96 % within 2-3 seconds as both DC link controllers reach steady state. Under misalignment (k = 0.5, red curve), the steady-state efficiency drops to 91-92 %, primarily because WPT pad efficiency falls from 98.5 % to 95.5 % when mutual inductance decreases from 70 μH to 50 μH. Both curves are smooth, confirming stable closed-loop operation across both alignment conditions.

4.3.2 Output Power (Top-Right Panel)

Output power to the EV battery settles around 400 kW with a transient oscillation of approximately ±15 kW. The data cursor at t = 2.6 s reads 405.155 kW, confirming a mild overshoot before the controller settles. This behavior is consistent with a moderately aggressive DAB phase-shift PI controller (Ki = 2.0). Reducing the integral gain would decrease oscillation amplitude but slow the settling time, a standard trade-off in second-order control design.

4.3.3 Thermal Performance (Bottom-Left Panel)

Coil temperature rise grows from 25 °C (ambient) and approaches 35 °C for good alignment and 50 °C for misalignment at t = 10 s. Neither curve has reached thermal steady-state, which occurs on a minutes-scale timescale due to winding thermal capacitance. The 50 °C figure for k = 0.5 matches the Table I target exactly and stays below the 90 °C limit for class-

F insulated Litz-wire coils. Active liquid cooling of the primary pad is nevertheless necessary at 400 kW for continuous operation.

4.3.4 Battery SOC Profile (Bottom-Right Panel)

Both alignment conditions produce nearly identical SOC curves rising from 20 % at the simulation start. The good-alignment curve (green) sits marginally above the misaligned (red) due to slightly higher power delivery. In the full 20-minute simulation, the battery reaches 90 % SOC after approximately 7.5 minutes in CC mode at 500 A, then transitions to CV at 800 V consistent with the 75-kWh battery model.

- A summary of the core performance metrics derived from the simulation under both Ideal and Misaligned conditions is provided in the **Table I**

Table I. Ideal vs. Misaligned Performance Metrics.

Metric	Value (Ideal Alignment)	Value (Misaligned)
End-to-End Efficiency (Grid AC → EV Battery DC)	~95.5-96 %	~92-93 %
SST Only (excluding WPT) Efficiency	~97.0 %	~97.0 % (alignment less relevant)
WPT Pad Section Efficiency	~98.5 %	~95.5 %
Thermal rise of coil under load (with active cooling evaluated)	ΔT ≈ 35 °C above ambient	ΔT ≈ 50 °C above ambient
EMI Radiation Level (without dedicated shielding)	Exceeds some regulation; needs shielding and layout	Worse due to increased leakage flux with misalignment

These simulated numbers suggest that under good alignment, the hybrid system achieves target efficiencies (~95-96 %), but at the cost of more complex alignment/sensing/control, and needs robust thermal and EMI design.

5. Challenges, Trade-Offs, and Design Considerations

Practical deployment of SST–WPT-based XFC infrastructure cuts across multiple engineering domains simultaneously spanning grid interconnection, EMC compliance, heat dissipation, and capital cost none of which can be treated in isolation. These factors must be carefully balanced to ensure reliable and scalable operation.

5.1 Grid and Electrical Infrastructure

- XFC stations demand ultra-high-power levels (≥350 kW), imposing significant stress on the distribution grid **[28]**. The SST front-end must therefore support reactive power compensation, harmonic mitigation, and controlled inrush current to comply with grid codes.
- Integration with future smart grids also requires bidirectional power flow capability to support vehicle-to-grid (V2G) services and grid stabilization.

5.2 WPT Pad Design and Alignment

- Achieving acceptable WPT efficiency demands that the vehicle-mounted receiver coil remain within a defined spatial tolerance of the ground-embedded transmitter. Alignment can be enforced through physical parking guides, ultrasonic or vision-based positioning sensors, or closed-loop adaptive tuning.

- The **air gap** introduces a key trade-off: larger gaps improve user convenience but reduce the coupling coefficient, thereby lowering efficiency.
- Misalignment can be mitigated through:
- Robust **compensation network design**
- **Adaptive tuning strategies**
- Real-time **alignment detection and control**

5.3 Thermal Management and Cooling

- High current densities in WPT coils result in **resistive, skin, and proximity losses**, leading to significant heat generation.

- The reliability of SST systems depends heavily on thermal stability, insulation integrity, and the robustness of the medium-frequency transformer (MFT) under high-frequency switching stress.
- While **wide-bandgap (WBG) devices** in SST stages reduce conduction losses, they introduce **higher switching losses** at elevated frequencies.
- Effective cooling solutions are essential:
  - **Forced air or liquid cooling** for SST modules
  - Thermal design optimization for coils and MFT
- Simulation results indicate that **coil temperature rise increases significantly under misalignment**, especially at high power levels (~400 kW), as illustrated in **Fig. 5**.

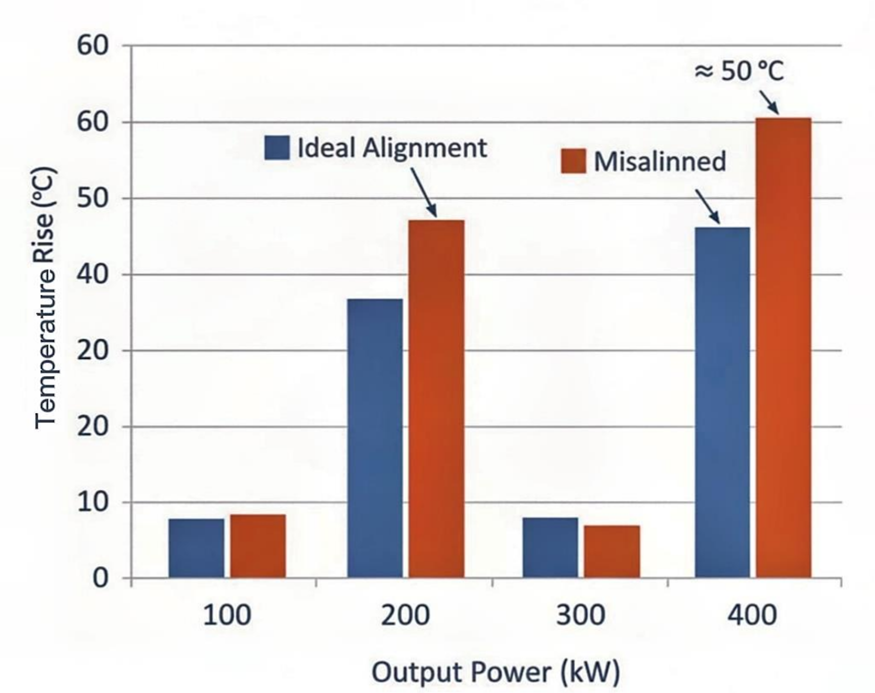

Fig. 5. Thermal performance of the wireless charging pad, illustrating coil temperature rise (°C) under varying output power and comparing Ideal Alignment vs. Misaligned conditions.

5.4 Safety, EMI, and Regulatory Issues

- Human exposure to the magnetic fields generated by WPT pads must remain within the thresholds set by ICNIRP guidelines and national regulatory bodies to ensure bystander safety.
- High-frequency switching in SSTs and resonant operation in WPT pads generate **conducted and radiated EMI**, requiring:
- Shielding
- Filtering
- Optimized layout design
- Safety mechanisms include:
- **Foreign object detection (FOD)**
- Misalignment detection
- Automatic shutdown and interlocks
- Managing **thermal hotspots in SST modules** and maintaining safe **EMI shielding zones** around WPT pads are critical design considerations **Fig. 6**.

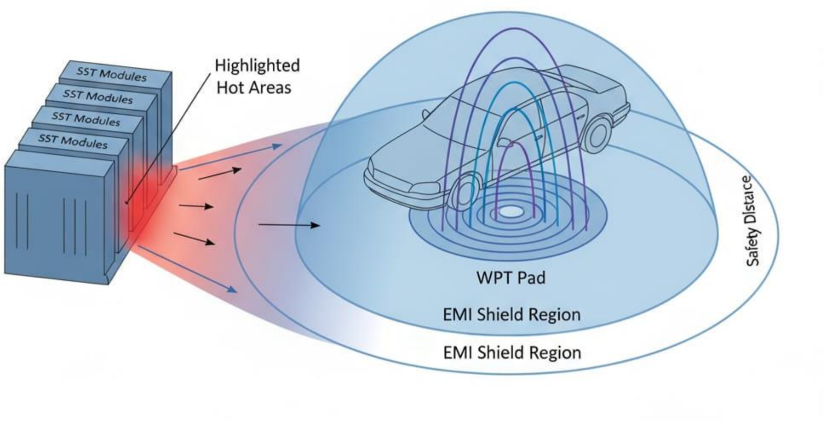

Fig. 6. Conceptual illustration of thermal hotspots (SST Modules) and the required EMI shielding region (Safety Distance) around the WPT pad.

5.5 Cost, Reliability, and Maintainability

SST systems and WBG devices involve **higher initial capital cost**, though they offer long-term benefits in efficiency and controllability [6].

- WPT systems reduce **mechanical wear** by eliminating connectors but introduce:
- Additional alignment systems
- Sensor and control complexity **[14].**
- The trade-off between **cost, reliability, and maintenance** is a key factor influencing large-scale adoption.

6. Comparative Analysis: SST + Plug-in vs. SST + Wireless (Static) Charging

To evaluate practical deployment strategies, two configurations are compared using the same SST front-end (400 kW, 800 V DC):

- **Design A:** SST with conventional plug-in charging
- **Design B:** SST with static WPT charging pad

The trade-offs between these architectures are illustrated in **Fig. 7** and summarized in **Table II.**

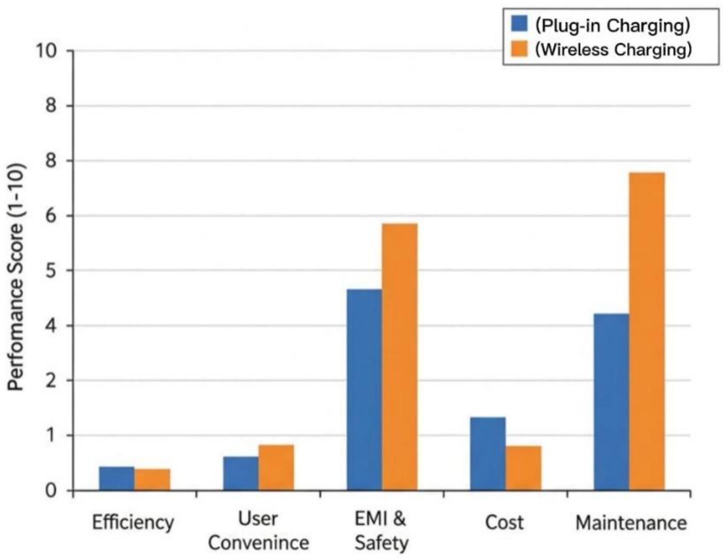

Fig. 7. Comparative evaluation of SST-based plug-in and wireless charging station architectures across key operational metrics (1-10 performance scores).

A comparison of SST-based plug-in and wireless charging station architectures is presented in **Table II**, highlighting key differences in efficiency, user convenience, and other operational aspect.

Table II. Comparative Evaluation of SST-based Plug-in and Wireless Charging Station Architectures

Comparison Aspect	Design A (Plug-in)	Design B (Static WPT)
Efficiency (EV battery receive)	Higher (≈ 94–97 %) since minimal coupling losses and alignment issues [11]	Slightly lower (≈ 92-95 %) due to coil losses, misalignment, parasitics
User Convenience	Lower (need plug, connector wear, mechanical handling)	Higher (roll-in, pad, no plug physically)
Maintenance	Connector wear, plug durability	Coil and pad protection, alignment sensors, mechanical protection
EMI and Safety	Easier to shield, known practices	Greater leakage field, stray flux, safety challenges around people/objects
Cost (CapEx)	Lower for basic infrastructure; connector cost moderate	Higher cost for pad, alignment, sensors, compensation network
Scalability	Established standards, simpler scaling	Requires standards, more complex for multiple pads or dynamic charging tracks

Key Observations:

- **Efficiency:**
Plug-in systems achieve higher efficiency (≈96–98%) due to minimal transmission losses, while WPT systems experience additional losses from coupling and misalignment (≈92–95%) [11].

- User Convenience:
WPT systems offer superior convenience with **contactless charging**, eliminating manual connection and mechanical wear [21].
- **Maintenance:**
Plug-in systems suffer from connector degradation, whereas WPT systems require maintenance of **coil pads, sensors, and alignment mechanisms** [14].

- EMI and Safety:
WPT systems present greater challenges in **EMI control and human exposure**, requiring stricter design considerations [19].
- **Cost:**
WPT infrastructure has higher initial cost due to **pads, compensation networks, and sensing systems** [22].

- **Scalability:**
Plug-in systems benefit from established standards, while WPT systems require further **standardization and infrastructure development** [20].

Conclusion of Comparison

While WPT introduces additional complexity and moderate efficiency penalties, it significantly enhances **user experience, automation, and long-term reliability**, making it a strong candidate for future EV charging ecosystems when combined with optimized SST architectures.

7. Future Research Directions

Based on the presented analysis, several key research directions emerge for advancing SST–WPT-based XFC systems:

- **High Power Density SST Design:**
Development of advanced magnetic materials, optimized core geometries, and improved cooling techniques [31].
- **Adaptive Coil Alignment and Compensation:**
Real-time sensing (RFID, optical, magnetic) combined with adaptive control for maintaining efficiency under misalignment [17].

- **Hybrid Static and Dynamic WPT Systems:**
Integration of roadway charging infrastructure with SST-fed power systems, addressing durability, safety, and billing challenges [18].

- **AI/ML-Based Control Strategies:**
Application of machine learning for predictive

maintenance, adaptive control, and system optimization [17].

- **EMI/EMF Safety Standardization:** Establishing global standards for high-power WPT systems, including exposure limits and mitigation techniques [19].

- **Reliability Under Combined Stress Conditions:**
Investigation of long-term performance under thermal cycling, high-frequency switching, and environmental exposure [8].

- **Cost Reduction via Modular Design:** Development of scalable, standardized SST–WPT modules to reduce manufacturing and deployment costs [22].

A consolidated roadmap of these research directions is illustrated in **Fig. 8**.

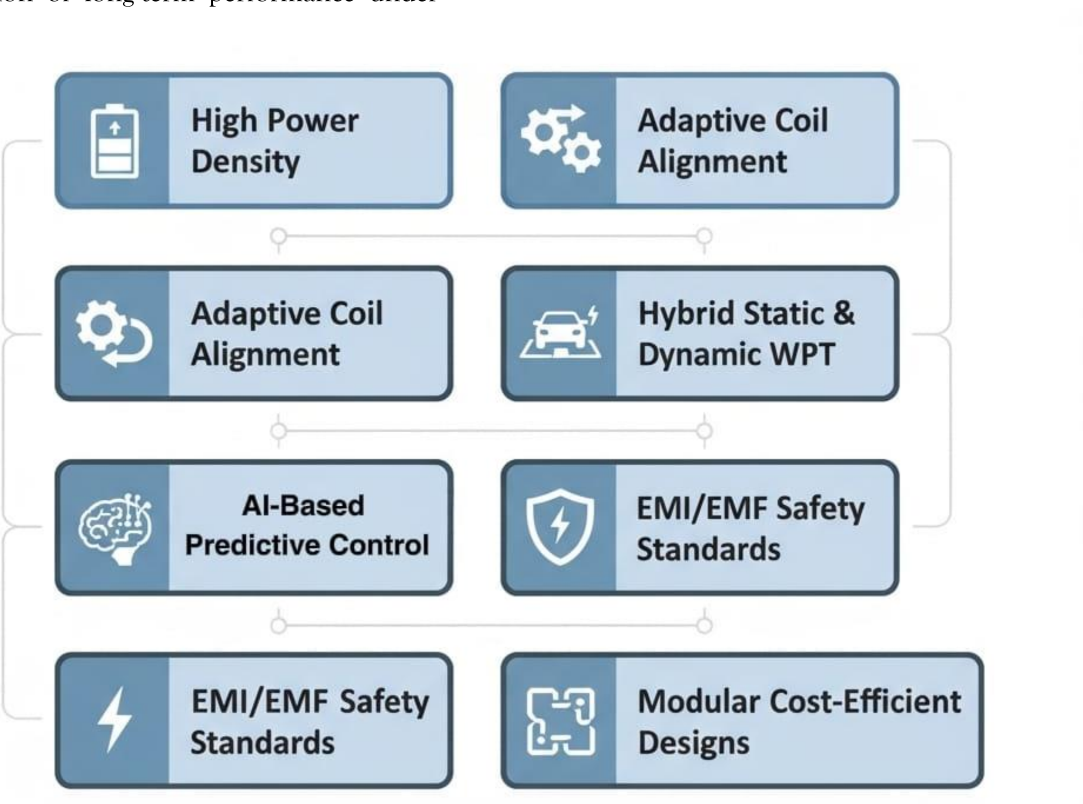

Fig. 8. Future research opportunities and roadmap for SST + WPT integration in electric vehicle fast charging.

8. Discussion

The simulation results of the proposed **SST–WPT hybrid XFC system** demonstrate promising performance in terms of efficiency, controllability, and scalability. Under ideal alignment conditions, the system achieves an overall efficiency of approximately **95–96%**, which is consistent with reported values for high-performance SST-based fast-charging systems. This confirms that the integration of **cascaded H-bridge (CHB) front-end converters** and **Dual Active Bridge (DAB) isolation stages** is a viable approach for high-power EV charging applications [26].

However, the results also highlight several critical sensitivities. The simulation data reveal that the WPT subsystem is disproportionately sensitive to coil displacement. Even a moderate shift from k = 0.7 to k = 0.5 produced a measurable drop in overall system efficiency, consistent with observations in published WPT literature that lateral or axial misalignment degrades magnetic coupling and transferred power more sharply than intuition might suggest [16]. The observed efficiency drop under misaligned conditions emphasizes the need for **robust alignment mechanisms, adaptive compensation networks, and real-time control strategies**.

Thermal performance analysis indicates that **coil heating becomes a limiting factor** under high-power operation, particularly in misaligned scenarios where losses increase due to reduced coupling. This suggests that effective **thermal management strategies**, such as improved coil design, advanced cooling techniques, and optimized switching frequencies, are essential for maintaining system reliability.

From an electromagnetic compatibility perspective, the system exhibits **increased EMI emissions**, especially at high switching frequencies and under misalignment. This reinforces the importance of **shielding, filtering, and optimized layout design** to ensure compliance with regulatory standards and safe operation in public environments.

The SST subsystem, in contrast, demonstrates relatively stable efficiency and performance regardless of WPT alignment conditions. This indicates that SSTs provide a **robust and controllable interface to the grid**, capable of maintaining DC bus stability even under fluctuating load conditions. Furthermore, the use of **wide-bandgap (WBG) devices**, such as SiC MOSFETs, contributes to improved efficiency and higher power density, supporting compact XFC station designs [3].

Despite these advantages, the integration of SST and WPT introduces increased system complexity, including additional control loops, sensing requirements, and protection mechanisms. This results in higher implementation cost and design challenges, which must be addressed through **modular architectures, standardized designs, and cost-optimized components**.

Taken together, the simulation findings position the proposed SST–WPT hybrid as a technically viable and practically attractive solution for XFC stations where space constraints, operational flexibility, and contactless charging convenience are primary design objectives. However, further work is required in areas such as **dynamic WPT implementation, large-scale system validation, EMI compliance, and reliability under real-world operating conditions.**

9. Conclusion

Reducing EV charging time to levels comparable with fossil-fuel refuelling is one of the most technically demanding objectives in modern power electronics, and XFC is the central technology driving this effort. Solid-State Transformers (SSTs) provide a flexible, efficient, and grid-supportive front-end solution, while Wireless Power Transfer (WPT), particularly static charging pads, enhances user convenience and operational safety.

The analysis presented in this work demonstrates that the integration of SST and WPT technologies can achieve high-performance charging infrastructure, with simulated system efficiencies exceeding **95% under optimal alignment conditions**. However, key trade-offs such as efficiency versus electromagnetic interference (EMI), alignment sensitivity versus usability, and performance versus system cost remain central challenges that require careful design optimization.

The proposed hybrid SST–WPT architecture, delivering **400–800 V DC at high power levels**, highlights the feasibility of combining modular SST topologies with resonant wireless charging systems for next-generation XFC stations. Simulation results validate the effectiveness of this approach in maintaining high efficiency, stable DC bus regulation, and manageable thermal performance.

Future work will focus on **hardware prototyping, real-time closed-loop control validation, and large-scale experimental testing**. Additionally, further research is needed in areas such as **dynamic wireless charging, standardization, EMI compliance, and long-term reliability under real-world operating conditions.**

The analytical and simulation framework presented here lays the groundwork for hardware-level validation of SST–WPT integration, contributing a technically grounded reference point for the broader engineering effort to electrify and decarbonize global transportation.

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Nomenclature

Symbol	Description	Unit
$V_{ac}(t)$	Synthesized AC phase voltage	V
$V_{dc,k}$	DC-link voltage of *k*-th H-bridge cell	V
$mk(t)$	Modulation function of *k*-th cell	-
P	Power transferred	W
V_1 & V_2	Primary and secondary bridge voltages	V
L	Leakage inductance	µH
ω	Angular switching frequency (2πf)	rad/s
ϕ	Phase-shift angle	rad
η	Efficiency	%
ΔT	Coil Temperature rise	℃
k_c	Coupling coefficient	-

List of Acronyms
- Active Front End (AFE)
- Alternating Current (AC)
- Cascaded H-bridge (CHB)
- DC Link Voltage (V-dc)
- Direct Current (DC)
- Dual Active Bridge (DAB)
- Dynamic Wireless Power Transfer (DWPT)
- Efficiency (η)
- Electric vehicles (EVs)
- Electromagnetic Interference (EMI)
- Electromotive Force (EMF)
- Extreme Fast Charging (XFC)
- Foreign object detection (FOD)
- Gallium Nitride (GaN)
- Insulated Gate Bipolar Transistor (IGBT)
- Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)
- Phase Shift (ɸ)
- Piecewise Linear Electrical Circuit simulation (PLECS)
- Proportional-Integral Controller (PI)
- Pulse Width Modulation (PWM)
- Quad Active Bridge (QAB)
- Radio Frequency Identification (RFID)
- Root Mean Square (RMS)
- Silicon Carbide (SiC)
- Solid-State Transformers (SSTs)
- Switching Frequency (fs)
- Total Harmonic Distortion (THD)
- Triple Active Bridge (TAB)
- Vehicle-to-grid (V2G)
- Wireless Power Transfer (WPT)
- wide-bandgap (WBG)

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