

Review article

Wireless power transfer systems with supercapacitor energy management: A comprehensive review

Zhixing Liu^{ID}*, Sadeeshvara Silva Thotabaddadurage^{ID}, Tek Tjing Lie^{ID}

Electrical and Electronic Engineering Department, School of Engineering, Computer and Mathematical Sciences, Auckland University of Technology, Auckland, New Zealand

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ABSTRACT

Wireless power transfer (WPT) provides a contactless and flexible energy delivery interface for supercapacitor-based and hybrid energy storage systems. However, unlike conventional resistive loads or batteries, supercapacitors exhibit continuously varying terminal voltage, voltage-dependent capacitance, and equivalent series resistance, which lead to dynamic reflected impedance at the WPT receiver. This impedance variation can shift the resonant operating point, degrade soft-switching conditions, and reduce power transfer efficiency during charging. This paper presents a comprehensive review of WPT-enabled supercapacitor and hybrid energy storage systems from a system-integration perspective. First, the interaction between WPT front-end characteristics and supercapacitor charging dynamics is analysed. Then, resonant compensation networks, inverter and rectifier interfaces, DC/DC conversion stages, and battery-supercapacitor hybrid architectures are systematically compared in terms of load shaping, efficiency, controllability, and scalability. Energy management and control strategies, including constant-current, constant-power, phase-shift, bilateral, model predictive, and intelligent control methods, are further reviewed with emphasis on dynamic impedance regulation and stable power coordination. Finally, key research gaps are identified, including adaptive impedance-aware control, thermal- and aging-aware energy management, predictive resonance tracking, and cross-layer co-design of WPT and storage interfaces. This review highlights that supercapacitors should be treated not merely as storage devices, but as dynamic impedance-shaping elements in WPT-based energy storage systems.

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* Corresponding author.

E-mail addresses: wkn1657@autuni.ac.nz (Z. Liu), sadeesh.silva@aut.ac.nz (S. Silva Thotabaddadurage), tek.lie@aut.ac.nz (T.T. Lie).

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1. Introduction

Wireless Power Transfer (WPT) has become a critical enabling technology for modern electrified systems, offering contactless energy delivery, enhanced user convenience, and improved operational reliability in environments where conventional conductive charging is impractical or undesirable [1]. Over the past decade, the proliferation of electric vehicles (EVs), mobile robotic platforms, autonomous manufacturing equipment, biomedical implants, and low-power Internet of Things (IoT) devices has dramatically broadened the application space for WPT systems [2]. Resonant inductive power transfer (IPT), operating typically in tens to hundreds of kilohertz, has demonstrated high efficiency and robustness for medium to high power scenarios, including automotive and industrial systems [3]. In contrast, capacitive power transfer (CPT), which leverages high-frequency electric fields in the megahertz range, offers advantages such as reduced electromagnetic interference, lower coil volume, and suitability for compact or metallic environments [4]. The corresponding field distributions of IPT and CPT systems are illustrated in Fig. 1.

The increasing maturity of high-frequency (>1 MHz) power electronics has even more accelerated WPT development. Advances in wide-bandgap semiconductor devices, soft-switching resonant inverters, compensation networks, and active rectification have enabled systems with improved efficiency, reduced losses, and greater tolerance to parameter variations [5]. Ongoing developments in dynamic EV charging lanes, automated warehouse logistics, and in-motion wireless power delivery for drones and automated guided vehicles (AGVs) have further established WPT as a strategic technology for future transportation and industrial automation systems [6]. As expectations rise, energy storage modules in these systems face more requirements, such as rapid charge, long cycle life, and reliability under large transient loads.

These increasingly demanding energy storage requirements have made supercapacitors (SCs) a promising solution because of their distinctive electrochemical characteristics. Unlike batteries, which store energy through faradaic reactions, supercapacitors primarily operate based on electrostatic charge accumulation in electric double layers or through pseudocapacitive surface processes [7]. This fundamental difference grants SCs exceptionally high-power density, fast charge-discharge capability, excellent round-trip efficiency (>95%), and long cycle life (often exceeding one million cycles) [8]. By comparison,

batteries generally provide higher energy density and longer-duration energy delivery, whereas SCs offer higher power density and faster transient response. These complementary characteristics provide the basis for battery-SC hybrid storage design, in which the required energy, peak power, cell voltage, capacity, permissible current, and converter ratings must be considered jointly [9]. These attributes make SCs particularly attractive in applications requiring rapid energy buffering, regenerative braking capture, pulsed power output, start-up power delivery, and frequent shallow cycling. SCs also tolerate high currents, mechanical vibration, and a broad range of operating temperatures, making them suitable for emerging WPT architectures with intermittent or dynamically varying charging profiles [10].

WPT inherently provides high-frequency, variable-amplitude power that aligns well with the fast charge-acceptance characteristics of SCs, enabling effective transient energy buffering and reduced stress on upstream converters. Evidence from battery-SC hybrid energy storage systems further shows that frequency-based power allocation can assign the low-frequency or average power demand to the battery and the high-frequency transient component to the SC [11]. Adaptive strategies can additionally modify the filter cut-off frequency and battery-current reference according to the operating condition and SC state of charge, thereby improving power allocation under dynamic loads [12]. In practical applications, SC-integrated WPT systems enhance performance across multiple domains, including DC-link stabilisation in EV charging, fast-charging support in robotics, and reliable energy storage in low-power or intermittent environments [13]. As a result, WPT-SC co-design has emerged as a promising approach for improving system efficiency, reliability, and robustness.

The development of WPT-SC systems can be traced through several representative stages. Early work by Madawala et al. employed dynamically reconfigurable SC banks in an inductively coupled power transfer system to suppress voltage transients and enable surge-free power transfer, with the SCs functioning primarily as auxiliary buffering and protection elements [14]. Subsequent research shifted towards receiver-side power conditioning and load adaptation. Fu et al. developed a cascaded boost-buck converter to provide impedance matching for resistive, battery, and ultracapacitor loads in a high-frequency WPT system [15]. Application-oriented studies then integrated wireless power links with hybrid battery-SC storage for implantable monitoring devices [16]. The research focus subsequently expanded towards direct and higher-power SC charging. Representative developments included

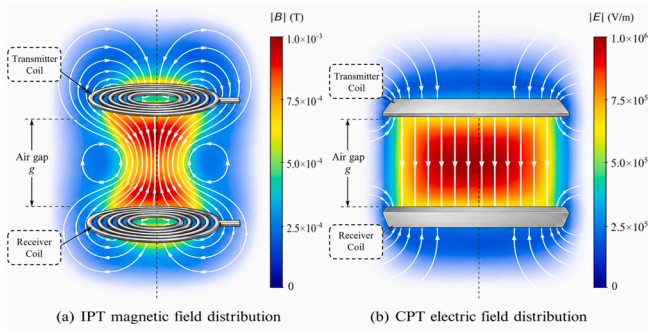


Fig. 1. Field distribution comparison between IPT and CPT systems.
Source: Adapted from [1,4].

a 3-kW constant-current WPT charger for a supercapacitor-powered sightseeing vehicle [17] and an LCC-compensated charging strategy that combined constant-current and constant-power operation to maintain high efficiency over the changing SC voltage range [18]. This progression reflects a transition from using SCs mainly as auxiliary power buffers to treating them as dynamic receiver-side storage loads whose voltage and equivalent impedance must be coordinated with the compensation network, rectifier, and charging controller.

However, several challenges remain. Dynamic coupling variations caused by misalignment, movement, or distance changes can alter mutual inductance or effective capacitance, leading to resonance shifts and reduced efficiency [19]. Frequency detuning further degrades performance, arising from component tolerances, parasitic effects, and nonlinear material behaviour, even under small deviations from the designed operating point [20]. The inherently time-varying voltage of SCs introduces continuously changing reflected load impedance, which alters the operating point and limits the effectiveness of conventional control strategies [21].

Additional nonlinearities arise from the voltage, temperature, and aging variations in SC capacitance and equivalent series resistance. Although advanced models exist, they are not yet fully integrated into WPT control and energy management frameworks. Consequently, the interaction between SC dynamics and WPT operation remains insufficiently explored.

Existing reviews related to this topic can be broadly divided into WPT-oriented and SC-oriented studies. WPT reviews mainly examine transfer mechanisms, compensation networks, coupler structures, converter topologies, control methods, and application-specific challenges [1,4,5]. SC-oriented reviews, by contrast, primarily address electrical characteristics, equivalent-circuit modelling, microgrid applications, hybrid storage, and cell-voltage equalisation [8,10,22]. These studies provide important foundations, but the WPT front-end and the dynamic storage subsystem are generally treated as separate research domains.

Table 1 compares the scope of representative reviews with that of the present work. The comparison focuses on whether the interaction among the resonant WPT link, receiver-side power conversion, dynamic SC impedance, and energy-management control is systematically considered.

Integrating WPT and SC technologies therefore constitutes a multi-domain problem involving power electronics, electromagnetic coupling, and energy storage dynamics. Existing studies typically address these aspects separately, leaving a gap for unified system-level analysis [24]. This review aims to bridge this gap by providing a comprehensive and structured perspective on WPT–SC system design and control.

The added value of the present review is therefore not simply the simultaneous discussion of WPT and supercapacitors. Instead, it

establishes a cross-layer relationship between the high-frequency resonant power-transfer stage and the time-varying storage subsystem. The SC terminal voltage, capacitance, ESR, rectifier operating state, and DC/DC control action are examined as factors that modify the effective impedance presented to the WPT link and consequently affect resonance, voltage gain, current stress, soft switching, and transfer efficiency.

The review further compares charging, control, and energy-management strategies according to their ability to accommodate the time-varying and nonlinear load characteristics introduced by supercapacitors.

This cross-layer perspective is used to compare IPT and CPT interfaces, inverter and compensation structures, rectification methods, SC-only and battery–SC architectures, charging profiles, impedance regulation, power-sharing strategies, and electrothermal- and aging-aware control. The present review is consequently positioned at the intersection of WPT power electronics, dynamic storage modelling, and coordinated energy management.

The scope of this review is restricted to near-field, power-electronics-based WPT systems, specifically IPT and CPT architectures interfaced with SC-only or battery–SC storage. Far-field RF or microwave transfer using rectennas, optical or laser power transfer, and ultrasonic power transfer are outside the present scope. These technologies employ substantially different propagation mechanisms, receiver-conversion interfaces, distance ranges, safety constraints, and power-management requirements. Their inclusion would therefore prevent a focused comparison of resonant compensation, reflected impedance, receiver-side conversion, and dynamic energy-storage control.

This paper is organised as follows. Section 2 introduces the fundamentals of near-field WPT and supercapacitors. Section 3 reviews representative application scenarios. Section 4 analyses power interfaces and compensation strategies. Section 5 discusses storage architectures. Section 6 reviews control and energy-management strategies. Section 7 identifies key research gaps and future directions, and Section 8 concludes the review.

A structured literature review was conducted using major scientific databases, including IEEE Xplore, Web of Science, and Scopus. The initial search yielded over 1300 records relevant to WPT–supercapacitor systems, such as architecture, power interface, and control strategies. After removing duplicates and applying selection criteria, approximately 180 key publications were selected for detailed analysis. These works were categorised into system architecture, power electronics interface, and control methods to structure the discussion. This methodology ensures a comprehensive and relevant review.

2. Background of wireless power transfer and supercapacitor applications

2.1. Fundamental principles of near-field wireless power transfer

IPT and CPT are the two near-field transfer mechanisms considered in this review. IPT transfers energy through magnetic coupling between transmitter and receiver coils [25]. Its coupling strength is commonly expressed through the mutual inductance

$$M = k\sqrt{L_p L_s} \quad (1)$$

where L_p and L_s are the transmitter and receiver self-inductances, respectively. Variations in alignment, separation, and coil geometry modify M and therefore alter the impedance reflected from the SC-side receiver to the transmitter [26].

CPT transfers energy through the electric field between coupling plates. Its coupling capacitance is affected by plate area, separation, fringing fields, misalignment, and the surrounding dielectric environment [27]. A fringing-field approximation is

$$C \approx \left[1 + 2.343 \left(\frac{d}{l} \right)^{0.891} \right] \frac{\epsilon l^2}{d} \quad (2)$$

Table 1

Comparison of representative reviews related to WPT and supercapacitor energy storage.

Review	Primary scope	Treatment of WPT and storage	Boundary relative to the present review
Zhang et al. [1]	General WPT mechanisms, couplers, power electronics, applications, and technical challenges	Broad WPT coverage; energy-storage dynamics are not a principal focus	Does not systematically connect SC voltage and impedance variation with receiver conversion, resonance, and charging control
Zhang and Mi [5]	Compensation topologies for high-power WPT systems	Detailed resonant-network analysis; storage behaviour is outside its principal scope	Does not examine compensation selection over the complete dynamic SC charging range
Wang et al. [4]	Basic and high-order CPT compensation networks	Detailed CPT circuit and compensation analysis; storage interfaces are not specifically considered	Does not address CPT–SC dynamic impedance interaction or coordinated receiver-side charging control
Berrueta et al. [10]	SC electrical characteristics, modelling, characterisation, applications, and future trends	Detailed treatment of SC behaviour; WPT power-conversion stages are outside its scope	Does not analyse how SC dynamics influence resonant-link efficiency, soft switching, or reflected impedance
Yang [8]	SC-only and hybrid SC energy-storage systems for microgrids	Covers SC storage configurations and microgrid applications; near-field WPT is not considered	Focuses on grid-level storage rather than high-frequency resonant power transfer and receiver interfaces
Liu et al. [23]	Preliminary review and simulation study of SC integration in WPT	Introduces representative WPT–SC configurations and simulated energy-buffering effects	Limited by conference-paper length and does not provide the present cross-layer comparison of CPT/IPT, rectification, thermal behaviour, aging, and advanced control
Present review	System-level integration of near-field WPT with SC-only and battery–SC storage	Connects IPT/CPT links, inverters, compensation, rectifiers, DC/DC interfaces, storage architectures, and control	Treats SC voltage, capacitance, ESR, and converter action as factors that modify reflected impedance, resonance, efficiency, charging behaviour, and energy management

Note: The absence of a topic indicates that it was outside the principal scope of the corresponding review rather than a shortcoming of that study.

Table 2

A qualitative comparison between CPT and IPT technologies.

Category	CPT (Capacitive Wireless Power Transfer)	IPT (Inductive Wireless Power Transfer)
Coupling Mechanism	Electric field coupling	Magnetic field coupling
Energy Transfer Medium	Displacement current between capacitor plates	Magnetic flux linkage between coils
Coupling Element	Coupling capacitors	Coupling inductors
Equivalent Circuit	AC source with coupling capacitors and compensation network	AC source with coupling inductors and compensation network
Compensation Topologies [28]	SS, SP, PS, PP, LCLC	SS, SP, PS, PP (same families), LCC
Operating Frequency	1 MHz to tens of MHz	10 kHz to 1 MHz
Coupling Coefficient (k)	$10^{-3} - 10^{-1}$ (weak coupling)	0.1–0.6 (strong coupling)
Transfer Distance [29]	Typically < 10 cm; limited by plate spacing	A few cm to tens of cm
Power Range	Typically operates in the range of several milliwatts to a few hundred watts, with most practical systems remaining below 3 kW	Typically operates from several watts to tens of kilowatts, with EV wireless charging systems commonly reported in the 3–20 kW range
Efficiency	70%–90%, up to 95% with proper tuning	70%–95%, remains high at elevated power levels
Alignment Sensitivity [30]	Highly sensitive to misalignment and tilt	Less sensitive due to wider magnetic flux distribution
Metal Environment Compatibility	Sensitive to nearby conductive objects and parasitic capacitance; additional shielding and insulation may be required	Conductive objects can introduce eddy-current loss and heating; magnetic shielding is commonly employed
Biological Safety	Safer owing to lower field intensity, suitable for implants	Generally safe; magnetic field is more localised
Electromagnetic Interference (EMI) [31]	Potentially high at MHz frequencies	Moderate EMI
Structure and Form Factor	Flat or flexible plate structure	Bulkier coil structure
Tuning Complexity	Higher, requiring precise impedance matching	Moderate with well-established design practice
Typical Applications	Biomedical implants, wearable electronics, metal-environment energy links and EV charging	EV charging, consumer electronics, robotics, industrial power transfer

Because CPT normally operates with relatively small coupling capacitance and high capacitive reactance, its voltage gain, insulation stress, and matching condition can be especially sensitive to changes in coupling and receiver-side impedance. Table 2 summarises the principal differences between IPT and CPT.

For SC-integrated systems, the distinction between IPT and CPT extends beyond the use of magnetic or electric fields. IPT generally provides a more mature route to medium- and high-power charging, but its performance remains sensitive to coil misalignment, magnetic shielding, and the coupling-dependent reflected load. CPT offers flatter and potentially lighter coupling structures, but its weaker coupling and higher operating frequency increase sensitivity to parasitic capacitance, plate-voltage stress, insulation, and rectifier capacitance.

In both cases, the rising SC terminal voltage modifies the rectifier and DC/DC operating point and consequently changes the effective impedance presented to the resonant network. CPT commonly requires

more precise matching and stronger management of voltage stress, whereas IPT generally offers higher power capability and more established control and interoperability practice. These differences define their respective application boundaries and motivate the separate IPT- and CPT-specific analyses in Section 4.

2.2. Supercapacitor fundamentals

Supercapacitors, also known as ultracapacitors or electrochemical capacitors, have become popular energy storage devices in power electronic systems because they offer high power density, fast charging and discharging, and long cycle life [32]. Unlike batteries, supercapacitors store energy by separating charges at interfaces or through quick surface redox reactions. This makes them well-suited for uses that require frequent and high-current charging, such as WPT systems.

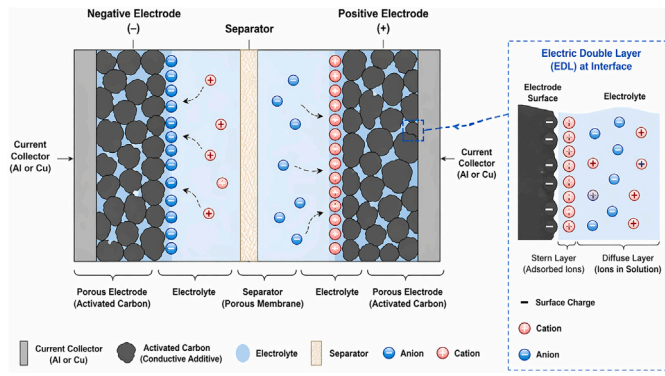


Fig. 2. Internal structure of an EDLC supercapacitor.
Source: Adapted from [33].

In an electric double-layer capacitor (EDLC), energy storage is achieved through charge separation at the electrode–electrolyte interface rather than electrochemical reactions. As illustrated in Fig. 2, the device consists of porous electrodes, an electrolyte, and a separator. When a voltage is applied, ions in the electrolyte accumulate at the electrode surfaces, forming electric double layers that enable energy storage. This physical mechanism allows for fast charge–discharge response and high power density, but also results in voltage-dependent and time-varying behaviour. Supercapacitors are generally divided into EDLC, pseudocapacitors, and hybrid types [34]. While their electrochemical mechanisms are different, their overall behaviour can be described with equivalent circuit models, which have been demonstrated in many papers. For this reason, this review looks at their electrical characteristics instead of focusing on material differences [35].

A key factor affecting the performance of supercapacitors is the equivalent series resistance (ESR), which represents the cumulative resistance of electrode materials, electrolyte, and internal connections. ESR directly influences conduction losses and thermal dissipation, particularly under high-current operation.

The dynamic response of a supercapacitor can be characterised by its time constant, defined as

$$\tau_{SC} = R_{ESR}C_{SC} \quad (3)$$

where C_{SC} denotes the effective capacitance [36]. Although SCs have very large capacitance, their low ESR enables rapid high-power response. Their electrical dynamics are generally much faster than the electrochemical and diffusion processes governing battery response.

In contrast, electrochemical batteries involve multiple electrochemical processes, including charge transfer and ion diffusion, which introduce distributed and often much larger effective time constants. As a result, batteries exhibit significantly slower transient responses compared to supercapacitors.

Various modelling approaches, including higher-order equivalent circuits and fractional-order models, have been proposed to capture the dynamic behaviour of supercapacitors. However, simplified models are generally sufficient for system-level analysis in WPT applications [37–39].

Unlike ideal resistive loads, supercapacitors exhibit nonlinear charging behaviour, especially under high current or wide voltage operating ranges [40]. For an ideal capacitor, the terminal voltage follows

$$V_C(t) = V_C(0) + \frac{1}{C} \int_0^t i_C(\tau) d\tau \quad (4)$$

In practical supercapacitors, both the effective capacitance and ESR vary with voltage, temperature, and aging, leading to deviations from linear behaviour. Consequently, the charging process becomes nonlinear and time-varying, which introduces additional challenges in system optimisation for WPT applications.

To sum up, adding supercapacitors as loads may change how WPT systems work. These effects influence resonance, power transfer efficiency, and control design, so system-level design is needed and will be discussed next.

3. Application scenarios of WPT–supercapacitor systems

WPT integrated with supercapacitor energy storage has been widely investigated in scenarios where high peak power, fast energy buffering, and frequent charge–discharge cycles are required. In such systems, the SC can serve as a primary energy buffer or as an auxiliary storage device to mitigate transient power demands, improve system efficiency, and reduce stress on batteries or power converters [41]. This section surveys major application domains and summarises representative system architectures and operational requirements. Table 3 summarises the typical application scenarios of WPT–supercapacitor systems, highlighting the functional roles of supercapacitors, associated benefits, and key challenges.

Beyond the application categories in Table 3, WPT–SC systems are also being investigated for IoT infrastructure, UAVs, marine systems, and railway applications. For the IoT perception layer, recent reviews emphasise high-degree-of-freedom magnetic coupling, multi-pickup charging, and system-level optimisation as important enablers for distributed sensor and edge-device networks [80].

Hybrid coupling is also emerging in UAV charging. A recent IPT–CPT hybrid system used CPT as the main transfer channel while reusing a compensation inductor as the IPT coupler. Frequency-variable re-configuration was employed to provide CC and CV operating modes and to improve tolerance to landing misalignment [81]. Such architectures may be particularly relevant when lightweight construction, compact integration, and wide-position charging are required. Marine and railway applications remain at an earlier stage and still require application-specific design and validation [82–88].

4. Power interface & compensation analysis

4.1. Comparative inverter topologies for dynamic WPT loads

The inverter stage plays a critical role in WPT systems by converting a DC input into an AC output for resonant energy transfer. Although inverter topologies are not specific to any energy storage technology, their operating characteristics strongly influence resonant behaviour, efficiency, and controllability of the WPT link, especially under dynamic load conditions [89]. Push–pull inverters provide low component count and simple gate driving and are therefore attractive for low-to medium-power systems, but the centre-tapped magnetic component and switch-voltage stress can limit wide-range operation [90,91].

Half-bridge inverters also use two switches and offer a compact implementation, although their lower available AC voltage and limited modulation freedom can make wide SC-voltage regulation dependent on a receiver-side DC/DC stage [92,93]. Full-bridge inverters provide higher excitation voltage and support frequency, phase-shift, and PWM control, making them more suitable for high-power WPT and dynamic reflected-impedance regulation [94].

Class-D, Class-DE, Class-E, and Class-EF structures target higher switching frequencies and soft-switching operation. Their reduced switching loss is attractive for compact IPT and CPT systems, but harmonic-tuned Class-E and Class-EF designs can be more sensitive to load and component variations [95]. The representative circuit structures and operating characteristics are summarised in Fig. 3 and Table 4.

Quantitative comparison across WPT–storage studies requires caution because reported performance depends strongly on power level, operating frequency, coupling condition, semiconductor devices, compensation parameters, storage voltage range, control bandwidth, and efficiency-measurement boundary. The following tables therefore adopt

Table 3
System-level roles and challenges of supercapacitors in WPT applications.

Typical scenarios	Role of SC	Key benefits	Key challenges	Citations
EVs, buses, AGVs	Transient buffering; peak power support; power smoothing	Mitigates coupling fluctuation; reduces battery stress; enables fast charging	Dynamic impedance variation; resonance detuning; coordination complexity	[42–55]
Robotics, rotating machinery, industrial systems	Local buffering; decoupling load dynamics	Stabilises supply; reduces peak demand; improves reliability	Highly dynamic loads; control complexity; impedance mismatch	[56–66]
IoT, wearable, biomedical devices	Intermediate storage; intermittent supply	Maintenance-free operation; long cycle life; stable output	Low coupling efficiency; limited power; miniaturisation constraints	[67–79]

Table 4

Comparison of representative operating characteristics of resonant inverter topologies used in WPT systems.

Topology	Switching type	Efficiency	Switching frequency
Class-D [96]	Soft-switching	High (85%–93%)	High to very high (100 kHz–10 MHz)
Class-DE [97]	Soft-switching	Very high (>95%, up to 97.3%)	High (~500 kHz)
Class-E [98]	ZVS	Very high (~95%)	Very high (over 1 MHz, up to 6.78 MHz)
Class-EF [99]	Harmonic-tuned	Very high (90%–95%)	Very high (1 MHz–15 MHz)

Note: The efficiency and frequency values represent ranges or operating points reported in different studies rather than results obtained under a common experimental benchmark.

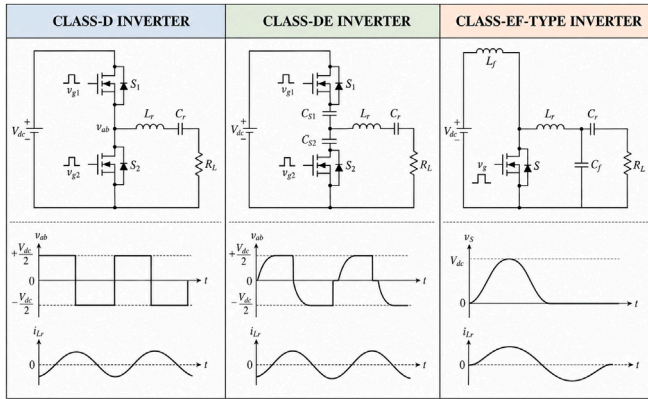


Fig. 3. System configuration of the Class-D, Class-DE and Class-EF inverters when duty cycle = 0.5.

selective quantification. Representative operating points are reported where they are explicitly available, while analytical voltage-drop and loss expressions are used for rectifier comparison. Architecture- and control-level metrics remain qualitative when the underlying studies do not use consistent definitions of round-trip efficiency, bandwidth, response time, or steady-state error.

4.2. IPT compensation networks: LCL, LCC, and double-sided LCC

To overcome the limitations of classical compensation networks, more advanced structures such as LCL, LCC, and double-sided LCC compensation have been extensively investigated [100].

4.2.1. LCL compensation

An LCL compensation network introduces an additional compensation inductor and capacitor to provide impedance transformation, current shaping, and reactive-power compensation. Because the exact input impedance depends on the specific LCL connection and receiver-side termination, a universal series-form impedance expression cannot be assigned to all LCL-compensated WPT systems.

For the conventional double-sided LCL topology considered in [101], one commonly used symmetric tuning condition is

$$\omega_0 L_1 = \omega_0 L_p = \frac{1}{\omega_0 C_1}, \quad \omega_0 L_2 = \omega_0 L_s = \frac{1}{\omega_0 C_2} \quad (5)$$

where L_p and L_s are the transmitter- and receiver-coil self-inductances, L_1 and L_2 are the corresponding compensation inductors, and C_1 and C_2 are the compensation capacitors. Under this tuning condition, the primary and secondary LCL tanks operate symmetrically at ω_0 , facilitating impedance transformation and near-zero reactive input under the intended operating condition.

4.2.2. LCC compensation

LCC compensation introduces additional reactive components that provide greater freedom for impedance transformation, coil-current regulation, and soft-switching design. In a double-sided LCC network, the transmitter side typically consists of the coupling-coil inductance L_p , compensation inductor L_{f1} , parallel capacitor C_{f1} , and series capacitor C_1 , with corresponding components L_s , L_{f2} , C_{f2} , and C_2 on the receiver side.

Under a conventional double-sided LCC tuning condition, the transmitter- and receiver-side resonant parameters satisfy [102]

$$\omega_0^2 = \frac{1}{L_{f1}C_{f1}} = \frac{1}{(L_p - L_{f1})C_1}, \quad \omega_0^2 = \frac{1}{L_{f2}C_{f2}} = \frac{1}{(L_s - L_{f2})C_2} \quad (6)$$

This condition illustrates the additional tuning freedom of the LCC network compared with first-order compensation. Under the ideal fundamental-harmonic approximation and nominal tuning, the resonant frequency is primarily determined by the compensation components rather than the load resistance or coupling coefficient. In practice, component tolerances, coil-inductance variation, parasitic parameters, and misalignment can perturb the tuned condition, so adaptive control or parameter optimisation may still be required.

4.2.3. Double-sided LCC compensation

With double-sided LCC compensation, both the transmitter and receiver use LCC networks. This setup improves impedance matching and makes the system less sensitive to changes in coupling and load. It is especially useful for high-power and dynamic WPT applications.

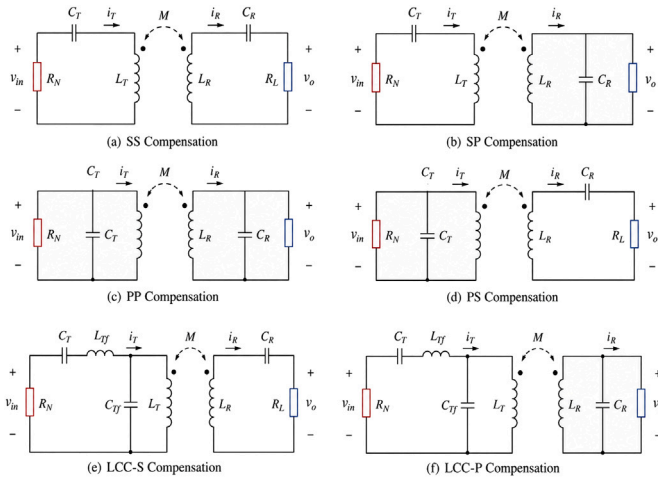


Fig. 4. Various kinds of compensation topologies for inductive power transfer [102].

4.3. Multi-coil compensation: Three-coil and four-coil structures

Multi-coil compensation structures, including three-coil and four-coil configurations, have been proposed to improve transfer distance and misalignment tolerance [103].

In a three-coil structure, an intermediate resonant coil is placed between the transmitter and receiver. The effective mutual coupling depends on the product of the coupling coefficients between each pair of adjacent coils [104]. In four-coil systems, the excitation and load coils are separated from the resonant interface, which allows for more flexible impedance transformation and greater robustness [105].

Recent WPT innovations have extended beyond conventional planar two-coil and multi-coil structures. Resonant passive shielding coils have been jointly optimised for leakage-field suppression, transfer efficiency, and shielding volume, demonstrating that electromagnetic safety improvement does not necessarily require a large efficiency penalty [106].

Cavity-resonator WPT provides another route to high-degree-of-freedom charging. Dual excitation can generate a rotating magnetic field that improves angular and positional coverage for omnidirectional receivers [107]. Metasurface-assisted WPT has also progressed from single-frequency designs to cross-frequency negative- and near-zero-permeability structures. Such structures can manipulate the near magnetic field at both kilohertz and megahertz frequencies to address the combined efficiency, distance, and leakage-field trade-off [108]. These developments illustrate that coupler, compensation, shielding, and field-control design are increasingly being optimised as an integrated electromagnetic system.

Table 5 and Fig. 4 compare representative compensation topologies with series- or parallel-compensated secondary networks.

Frequency modulation (FM) is commonly employed to regulate transferred power by detuning the operating point from resonance. Under frequency deviation $\Delta\omega$, the impedance of a series-compensated network becomes:

$$Z(\omega) = j\omega L - \frac{j}{\omega C} \quad (7)$$

This approach directly changes the resonant-tank impedance and current magnitude [111]. In contrast, phase-shift (PS) modulation, especially in full-bridge inverters, controls power flow by adjusting the effective fundamental voltage applied to the resonant tank, while keeping the operating frequency constant [112].

4.4. CPT-specific compensation and receiver-side considerations

Unlike IPT systems, CPT systems transfer power through relatively small coupling capacitances formed between transmitter and receiver plates. The resulting large capacitive reactance, together with variations in plate separation, misalignment, and surrounding dielectric conditions, makes CPT systems particularly dependent on resonant compensation. Representative approaches include double-sided LC, LCL, LCL-L, LCLC, CLLC, and multistage matching networks. These topologies provide different trade-offs among voltage gain, reactive-power circulation, component stress, load tolerance, and implementation complexity.

The selection of compensation becomes more critical when the CPT receiver supplies a supercapacitor. During charging, the increasing SC terminal voltage changes the operating point of the rectifier and downstream converter, thereby modifying the equivalent AC-side impedance presented to the resonant network. This variation can alter the charging current, voltage gain, resonant current, soft-switching margin, and electric-field stress. Consequently, a compensation network designed for a fixed resistive load may not maintain satisfactory performance over the full SC charging range.

Table 6 compares representative CPT compensation approaches using reported experimental power and efficiency data. In general, lower-order networks offer simpler implementation but greater sensitivity to load and coupling variations, whereas higher-order and multistage networks provide improved impedance-transformation flexibility at the expense of additional resonant components and more complex tuning. For wide-range SC charging, the compensation network should therefore be coordinated with the rectifier, DC-link regulation, and storage-side DC/DC converter rather than designed independently.

4.5. Comparative receiver rectifiers for WPT-SC systems

The receiver rectifier determines the conduction loss, output regulation capability, and effective impedance presented to the resonant WPT link. Diode bridges are simple, inexpensive, and robust, but their fixed voltage drop is disadvantageous for low-voltage, high-current SC charging [119]. Synchronous rectifiers replace the diodes with controlled MOSFETs and can substantially reduce conduction loss, although accurate timing and gate-drive coordination are required [120].

Active rectifiers provide an additional control degree of freedom by regulating the switching instants or phase relationship. They can support output-voltage regulation, bidirectional power flow, and receiver-side impedance shaping, but require sensing, synchronisation, and stability analysis [121]. As the SC voltage rises, the rectifier and downstream converter operating point changes; the rectifier should therefore be selected together with the compensation network and charging controller rather than as an independent conversion stage.

Representative rectifier structures and their principal trade-offs are summarised in Fig. 5 and Table 7.

4.6. Load sensitivity and matching in resonant WPT front ends

In resonant WPT systems, the effective load impedance at the resonant tank mainly determines the operating point, power transfer efficiency, and soft-switching. When supercapacitors are added to the receiver, the load is no longer a fixed resistor. Instead, the resonant front-end faces a load that changes with voltage and time, which directly impacts resonance and system performance [129].

As a supercapacitor charges, its terminal voltage keeps rising, which causes the equivalent load seen by the resonant network to change over time [130]. Even with constant-current charging, the effective load impedance goes up as the supercapacitor voltage increases.

The ESR of the supercapacitor also adds a resistive part to the load. This resistance changes with temperature, state of charge, and aging, which further affects the load seen by the resonant front-end [131].

Table 5
Reflected impedance characteristics of representative IPT compensation topologies under resonant operation.

Compensation networks	Reflected resistance $\Re(Z_r)$	Reflected reactance $\Im(Z_r)$	Quality factor (Q_s)
SS	$\frac{\omega_0^2 M^2}{R_L}$	0	$\frac{\omega_0 L_s}{R_L}$
SP	$\frac{R_L M^2}{L_s^2}$	$-\frac{\omega_0^2 M^2}{L_s}$	$\frac{R_L}{\omega_0 L_s}$
PS	$\frac{\omega_0^2 M^2}{R_L}$	0	$\frac{\omega_0 L_s}{R_L}$
PP	$\frac{R_L M^2}{L_s^2}$	$-\frac{\omega_0^2 M^2}{L_s}$	$\frac{R_L}{\omega_0 L_s}$
LCC-S [109]	$\frac{\omega_0^2 M^2}{R_L}$	0	$\frac{\omega_0 L_s}{R_L}$
LCL-P [110]	$\frac{R_L M^2}{L_s^2}$	$-\frac{\omega_0^2 M^2}{L_s}$	$\frac{R_L}{\omega_0 L_s}$

Table 6
Comparison of representative CPT compensation approaches and their implications for supercapacitor charging.

Approach	Reported performance	Implications for varying SC-side load	Advantages	Limitations
Double-sided LC [113]	109–112 W; 70.6%–74.8% dc–dc efficiency	Provides load-independent CC and CV frequencies, although charging current and efficiency still vary with the SC-side load	Low component count; simple design; inherent CC/CV operation	Sensitive to coupling variation; possible over-power condition; relatively low reported efficiency
LCL [114]	1.88 kW at 85.87% efficiency; 150 mm air gap	Voltage-source output is suitable for a regulated downstream converter, but direct SC connection causes current variation	Kilowatt-level operation; compact four-plate coupler; few components	High plate-voltage stress; reduced power and efficiency under misalignment
LCL-L [115]	1.5 kW at 85.5%; above 76% under severe coupling variation	Transferred power decreases with reduced coupling or increased SC-side impedance	Four resonant components; near-ZPA/ZVS; limits excessive power	High coupler RMS voltage; load-dependent efficiency; insulation requirements
Double-sided LCLC [116]	1.6–2.4 kW; 89.1%–90.8% dc–dc efficiency	Additional design freedom improves tolerance to coupling and storage-side load variation	High power; unity input/output power factors; reduced voltage stress	Eight resonant components; complex tuning; increased circulating reactive energy
CLLC [117]	Approximately 2.9 kW input at 1 MHz	Flexible impedance transformation can reduce sensitivity over a specified SC charging range	Kilowatt capability; flexible gain; potential ZVS and lower reactive power	Complex resonant modes; difficult parameter design; high voltage stress
Multistage L-section [118]	193–557 W; approximately 82% to above 90% at 6.78 MHz	Multiple matching stages improve gain and efficiency tolerance under load and coupling variation	High MHz-frequency efficiency; flexible gain; modular implementation	Requires high-Q components and careful parasitic design; limited wide-range adaptation without active tuning

Note: The reported values were obtained under different frequencies, coupler dimensions, air gaps, loads, devices, rectifiers, and efficiency boundaries. They indicate demonstrated performance rather than directly comparable topology-level benchmarks. The cited prototypes did not necessarily employ supercapacitor loads. The SC-side implications are inferred from the reported load, coupling, gain, and impedance characteristics of each topology.

Table 7
Comparison of representative rectification architectures and their voltage-drop and conduction-loss characteristics.

Type	Topology	Elements	Output voltage (V_{dc})	Conduction loss (P_{cond})	Advantages	Limitation	Scenario
Diode [127]	Half-wave	$1 \times D^a$	$V_{dc} \approx V_M - V_f$	$P_{cond} \approx V_f I_{dc}$	Simple, low cost	High ripple, low efficiency	Low power
	Full-wave	$2 \times D, 1 \times C^b$	$V_{dc} \approx V_M - V_f$	$P_{cond} \approx V_f I_{dc}$	Low loss	Complex system	Low frequency
	Full-bridge	$4 \times D$	$V_{dc} \approx V_M - 2V_f$	$P_{cond} \approx 2V_f I_{dc}$	Most common, robust	Low efficiency at low voltage	High voltage
Sync [120]	Voltage multiplier	Multi $D, 1 \times C$	$V_{dc} \approx 2V_M - 2V_f$	Mainly from diode drop and ESR loss	Increase voltage	Low efficiency at high current	CPT/high frequency
	Full-bridge	$4 \times M^c$	$V_{dc} \approx V_M - 2I R_{ds(on)}$	$P_{cond} \approx I_{rms}^2 R_{eq}$	High efficiency at high current	Gate driving required	Rapid charging
	Self-driven	M +auxiliary network	$V_{dc} \approx V_M - 2I R_{ds(on)}$	$P_{cond} \approx I_{rms}^2 R_{ds(on)}$	Simplified driving	Narrow frequency range	Medium power
Active [128]	PWM control	Full-bridge+control	V_{dc} can be adjusted	$P_{sw} \approx 0.5V_{ds} I_d (t_r + t_f) f_s$	Output regulation	Complex control, high switching loss	Wide range
	Bidirectional	Bidirectional full-bridge	Can reverse power	$P \approx P_{cond} + P_{sw}$	Strong system flexibility	EMI/protection required	Energy recovery, V2G

^a Diode.

^b Center-tap.

^c MOSFET.

Rectifier Topologies for WPT Receivers: From Passive to Fully Controlled

	1. DIODE BRIDGE RECTIFIER (Passive Rectifier)	2. SYNCHRONOUS RECTIFIER (Active Switches, Unidirectional Power Flow)	3. ACTIVE RECTIFIER (Controlled Rectifier, Bidirectional Power Flow)
CIRCUIT DIAGRAM			
POWER FLOW	Unidirectional Power Flow (AC → DC)	Unidirectional Power Flow (AC → DC)	Bidirectional Power Flow (AC ↔ DC)
KEY FEATURES	- Passive operation - High conduction loss ($\approx 2V_D$) - Unidirectional power flow - No output regulation	- Low conduction loss ($R_{DS(on)}$) - Reduced reverse recovery loss - Unidirectional power flow - No output regulation	- Low conduction loss - Controllable output (V_{dc}, I_{dc}) - Bidirectional power flow - Fast dynamic response
TYPICAL WAVEFORMS			
APPLICATION CONTEXT (Example)	Simple Receivers Low-Cost Systems Low Power Rating	Improved Efficiency Mid-High Power Systems Energy Storage (SC, Battery)	Bidirectional Systems Fast Charging / Discharging Advanced Energy Management

L_s : Secondary Inductance C_{dc} : DC-Link Capacitor R_L : Load / Supercapacitor v_{ac} : AC Voltage i_{in} : Input Current V_{dc} : DC Output Voltage ϕ : Phase Shift

Fig. 5. Comparison of diode bridge, synchronous, and active rectifier topologies for WPT receiver systems. [122–126].

Changes in load impedance affect both the quality factor and how current is distributed in the resonant tank. In a typical series-compensated network, the quality factor is given by:

$$Q = \frac{\omega_0 L}{R_{eq}} \quad (8)$$

where ω_0 is the nominal resonant angular frequency and L is the equivalent inductance [132]. As R_{eq} increases during SC charging, the quality factor decreases, leading to reduced tank current, altered voltage stress, and increased sensitivity to detuning.

These changes can make soft-switching at the inverter less effective, which leads to higher switching losses and lower efficiency. Experimental studies have found that efficiency drops and device stress increases when resonant systems run with large load changes and no adaptive measures [133].

Many WPT systems use frequency modulation to control how much power is transferred. But if load changes have already shifted the operating point, more frequency detuning can make efficiency losses worse. In a series resonant tank, (9) shows that both load impedance and reactive detuning affect power transfer together.

$$I(\omega) = \frac{V_{in}}{\sqrt{R_{eq}^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \quad (9)$$

Accordingly, maintaining near-resonant operation over a wide load range is important for WPT systems subject to dynamic receiver-side conditions [134]. Tuneable compensation elements, like switched capacitor banks or variable inductors, allow real-time adjustment of resonant parameters [135]. Front-end impedance shaping, using controlled rectification or coordinated DC–DC interfaces, helps stabilise the load seen by the resonant tank [136,137].

These methods help maintain soft-switching and high efficiency in the resonant front-end. A more detailed discussion of load shaping can be found in Section 5.

5. Energy storage architecture in WPT-SC system

As discussed in Section 4, the resonant WPT front-end does not directly interact with an ideal load. Instead, it perceives an equivalent reflected impedance determined by the rectifier, DC-link, and energy storage subsystem. In practical WPT–SC systems, the storage fundamentally decides how the impedance changes during operation process.

The storage-interface implications are not identical for IPT and CPT systems. In IPT systems, the comparatively stronger magnetic coupling and established compensation practice generally provide greater tolerance to receiver-side load variation. In CPT systems, the smaller coupling capacitance, higher operating frequency, and larger reactive voltage gain can make the resonant link more sensitive to the equivalent impedance presented by the rectifier and storage subsystem. Consequently, direct supercapacitor charging places more stringent requirements on compensation tuning and device-voltage management in CPT systems. A regulated DC link or an intermediate bidirectional DC/DC converter is therefore particularly valuable for decoupling the CPT resonant network from the wide supercapacitor voltage range.

From a system perspective, the energy storage part can be viewed as a load shaping layer, located between rectifier and the actual energy consuming devices like motors. This layer consists of rectifier stage, DC-link capacitor, DC/DC converters and energy storage elements (battery, supercapacitor or hybrid). A generalised structure of this layer is shown in Fig. 6.

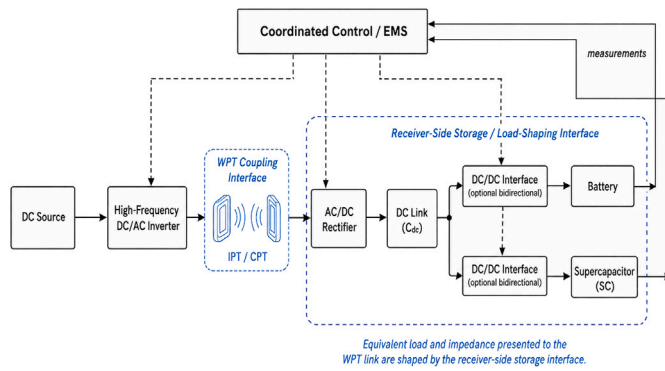


Fig. 6. Diagram of WPT energy storage part.

This section systematically reviews storage architectures in WPT-SC systems, highlighting how different systems influence load sensitivity, control complexity, and system-level performance.

5.1. Battery-only system

In conventional battery-only energy storage architectures, the load is typically supplied directly by the battery through power electronic interfaces. Such systems generally exhibit relatively slow dynamic response due to electrochemical reaction limitations and are less capable of handling rapid power fluctuations.

In contrast, WPT systems integrated with supercapacitors introduce an additional buffering layer that decouples the wireless power transfer front-end from the load demand. This enables fast transient response, improved power smoothing, and reduced stress on the battery when hybrid storage is employed.

Therefore, the design of energy storage architecture in WPT-SC systems is fundamentally different from that of battery-only systems, requiring coordinated consideration of power buffering, dynamic load shaping, and multi-timescale energy management.

5.2. SC-only system

Supercapacitor-only systems represent the simplest integration form of WPT and energy storage. These architectures are commonly adopted in applications emphasising high power density and short-duration energy buffering.

5.2.1. Direct rectified-to-SC charging

In the simplest setup, the rectified output connects straight to the supercapacitor bank, so there is no DC/DC regulation converter used. This architecture minimises the number of conversion stages and provides a simple and cost-effective implementation. However, as the SC terminal voltage changes during charging, the operating point of the rectifier and the equivalent impedance presented to the resonant WPT link also vary. This variation can move the system away from its designed impedance-matching and soft-switching conditions, leading to increased loss or reduced power transfer if no adaptive regulation is employed [127]. Because the structure is simple, it cannot support complex control strategies. Typical control focuses on constant current (CC), voltage ceiling protection, and thermal management. This setup is used for opportunity charging, pulse power support, and short-range industrial buffering [138].

5.2.2. SC with DC/DC regulation

To reduce load variability, many systems place a DC/DC converter between the rectifier and the supercapacitor. This setup offers regulated charging current or voltage and improves the stability of the resonant front-end.

In wireless power transfer systems, receiver-side controlled power-electronic interfaces, including semi-active rectifiers and regulated DC/DC converters, can shape the effective impedance presented to the resonant link and reduce its sensitivity to storage-side voltage variation [136].

In SC charging systems, a downstream DC/DC converter additionally provides explicit regulation of charging current or voltage.

5.2.3. SC banks and series-parallel balancing

In high-voltage or high-capacity systems, multiple supercapacitor cells must be arranged in series-parallel configurations. This introduces additional design considerations, including voltage balancing, cell mismatch, thermal gradients and aging issues. Some papers employed balancing circuits, either passive or active, to prevent over-voltage stress on individual cells.

5.3. Hybrid storage (Battery + Supercapacitor)

Hybrid energy storage systems (HESS) combining batteries and supercapacitors are widely investigated to balance energy density and power density requirements [139].

This subsection categorises hybrid architectures according to power coupling structure, which directly determines load shaping behaviour.

5.3.1. Passive parallel hybrid

In passive parallel configurations, the battery and supercapacitor are directly connected to a common DC-link. This topology is simple and cheap. However, it still suffers from power sharing and uncontrolled current distribution. Because no active decoupling exists, the WPT front-end perceives a composite impedance that varies with both battery and SC states.

5.3.2. Series/cascaded hybrid

In cascaded setups, the supercapacitor is connected in series with the battery or DC-link to help meet sudden power demands. The supercapacitor manages high-frequency transients, while the battery provides steady energy.

This setup lowers the peak current drawn from the battery, but it can also create extra challenges for managing voltage [140].

5.3.3. DC/DC-decoupled hybrid

In this setup, both the battery and supercapacitor connect to the DC-link using separate bidirectional DC/DC converters.

5.3.4. Synchronous battery-SC charging

A further hybrid interface is synchronous battery-SC charging, in which the two storage devices are charged simultaneously from a common DC source. A single-input multi-output cascaded buck converter can provide separate charging branches for the battery and SC while sharing the same input bus [141]. Cascaded current and voltage control allows each branch to follow its own charging-current and terminal-voltage limits, thereby accommodating the different electrical characteristics of the two storage devices.

5.3.5. Multi-port converters

Multi-port converters integrate WPT-rectified DC, battery, and supercapacitor into a single power conversion structure.

Table 8 compares all these energy storage architectures.

5.3.6. Battery lifetime enhancement evidence

The principal battery-lifetime benefit of a battery-SC HESS arises from reducing rapid and high-amplitude battery-current variations. When transient power demand and sudden charging-current changes are assigned to the SC, the battery can operate with a smoother, lower-frequency current profile. This reduces battery peak current, RMS current, current ripple, and short-duration electrothermal stress.

A PV-fed multi-output converter study demonstrated this principle by using the SC converter to accommodate power variation while applying extended current control to the battery-converter branch [142]. The control scheme was designed to suppress abrupt battery charging currents that contribute to capacity loss and cycle-aging stress.

The same principle is relevant to WPT-HESS systems. Coupling variation, receiver-power fluctuation, and load transients can be buffered by the SC branch, while the battery-current reference is allowed to change more gradually. However, the achievable lifetime benefit depends on the selected power-sharing bandwidth, battery-current limits, state-of-charge window, temperature, depth of discharge, and converter efficiency. The presence of an SC alone therefore does not guarantee battery-life extension; effective current allocation and storage-side control are essential [143].

Fig. 7 is presented as a conceptual trend diagram that synthesises the qualitative load-sensitivity relationships discussed in Sections 4.1–4.3. It is not generated from a unified simulation, experimental platform, or normalised literature dataset.

The diagram illustrates that compensation networks and inverter topologies with greater impedance-transformation or modulation flexibility may retain their preferred operating conditions over a wider SC-side load range. By contrast, lower-order or less controllable configurations may exhibit greater sensitivity to the operating-point variation produced during SC charging. The curves indicate relative tendencies only; no absolute efficiency value or quantitative difference between topologies should be inferred from the figure.

5.4. Multi-source WPT charging architectures

Beyond single-source systems, WPT-SC architectures increasingly integrate multiple energy sources to improve flexibility and efficiency.

5.4.1. PV + WPT + SC

In PV-assisted systems, photovoltaic output is fluctuating and is buffered by supercapacitors before or after the WPT stage. SCs absorb rapid irradiance-induced power variation, stabilising the WPT input or output stage [144].

5.4.2. Grid + WPT + Battery + SC

In grid-connected charging stations, station-side SC buffers can reduce short-duration grid-power peaks, while vehicle-side hybrid storage can smooth the dynamic load presented to the wireless charger. Coordinated energy management is therefore required across the grid, stationary storage, WPT interface, and vehicle-side storage [145].

6. Energy storage control strategies

6.1. Control hierarchy in WPT storage system

Regulating power flow in resonant WPT systems requires balancing efficiency, stability, and soft-switching. Unlike standard converters, resonant WPT front-ends are highly affected by the coupling coefficient, load changes, and compensation settings, which makes control design more complex.

Frequency modulation (FM) is one of the most commonly used methods for regulating transferred power in resonant WPT systems. Adjusting the operating frequency near resonance can change the effective impedance and tank current without changing the hardware. FM is often used in diode-rectified systems and simple designs [148]. However,

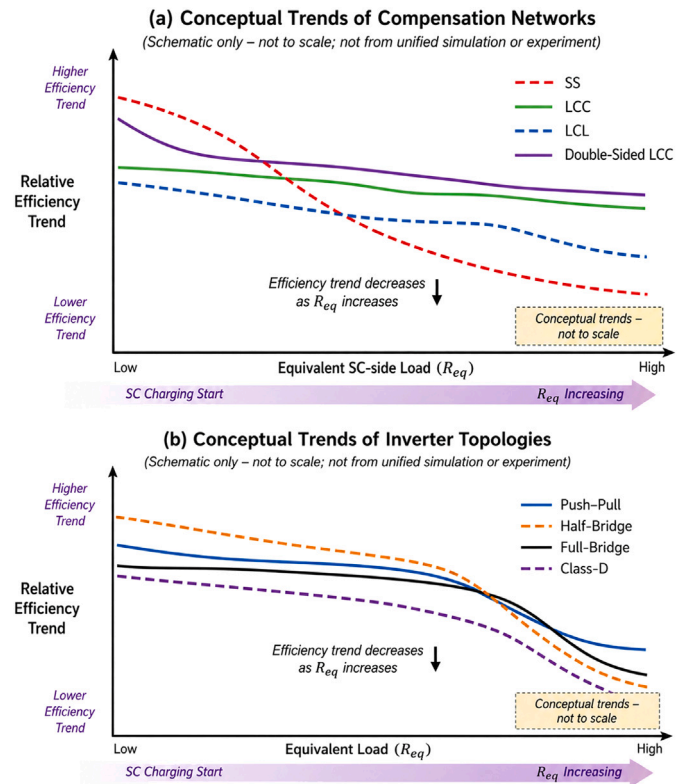


Fig. 7. Conceptual trend diagram illustrating the relative sensitivity of representative WPT-SC configurations to increasing SC-side equivalent load: (a) compensation-network trends and (b) inverter-topology trends. The curves are schematic and are not derived from a unified simulation or experimental dataset.

detuning the frequency too much can increase reactive currents and may affect soft-switching, especially when the load changes quickly.

PWM and phase-shift control are other ways to regulate power, especially in full-bridge inverter setups. With phase-shift control, the phase angle between the bridge legs sets the main excitation voltage, while the switching frequency stays the same. This method usually keeps resonant conditions better than frequency detuning and is often used in high-power systems for electric vehicles.

Recently, more focus has been given to bilateral control, where both the transmitter and receiver help regulate power [149]. Active rectifiers or DC/DC converters on the receiver side can adjust the reflected impedance, allowing for better control and more tolerance to misalignment and load changes. These dual-side control methods are especially useful when the supercapacitor voltage changes quickly.

Some applications, like vehicle-to-grid (V2G), now require bidirectional power flow [150]. Bidirectional WPT needs careful coordination between the inverter and rectifier to keep the system stable and maintain soft-switching, even when power flows in reverse.

Together, these power flow control methods make up the first level of regulation in WPT-supercapacitor systems. However, how well they work depends a lot on how the storage system charges afterwards.

6.2. Charging control for supercapacitors

Controlling how supercapacitors charge in WPT systems is getting more attention because their electrical properties change quickly. As a result, it becomes challenging to keep resonance conditions optimal, maintain stable power flow, and ensure soft-switching during charging [151].

Table 8

System-level comparison of representative energy-storage architectures used in WPT systems.

Architecture	Load stability	Control flexibility	Battery protection	Complexity	Scalability	Recommended use	Typical application or demonstrated scale
SC-only [23]	Low	Low	N/A	Very low	Low	Low-power	CPT systems, IoT devices (W–100 W)
SC + DC/DC [146]	Medium	Medium	N/A	Medium	Medium	Medium-power	IPT systems, EV auxiliary charging (100 W–kW)
Passive hybrid [9]	Low	Low	Moderate	Low	Medium	Cost-sensitive	Low-power IPT/CPT (10 W–500 W)
DC/DC hybrid [12]	High	High	High	High	High	High-performance	EV charging, industrial WPT (kW–tens of kW)
Synchronous multi-output hybrid [141]	High	High	High	High	Medium	Simultaneous battery–SC charging	Receiver-side WPT–HESS charging; power level is converter-dependent
Multi-port [147]	Very high	Very high	Very high	Very high	High	Research-level	Multi-source grid WPT (kW+)

Note: Architecture-level round-trip efficiency, control bandwidth, and transient response are not assigned as universal numerical ranges because they depend on the WPT-link boundary, converter topology, storage sizing, controller design, operating power, and disturbance definition. The entries therefore describe relative system-level characteristics. Any power levels shown represent reported application scales rather than common benchmark ranges.

In early WPT systems, supercapacitors were often charged by directly transferring rectified energy, without controlling the charging process. Although this method keeps the system simple, it can put a lot of stress on semiconductor devices and increase losses in the resonant network [152]. As the SC voltage rises, the equivalent load presented to the WPT front-end changes, moving the system away from its designed impedance-matching and soft-switching conditions. Depending on the compensation topology and parasitic parameters, the phase and apparent resonant operating point may also vary.

To address these problems, many systems now use constant-current (CC) charging strategies. In CC-controlled WPT systems, either the transmitter converter or a DC–DC stage keeps the charging current at a set value. This can be done by adjusting the frequency, phase, or duty cycle, depending on the resonant circuit used. This means the resistive part seen by the rectifier changes as charging continues. As a result, keeping constant current may require more control effort later in the process. If not managed well with resonance tracking, this can lead to higher circulating currents or more switching losses in the inverter.

Constant power (CP) charging is a newer approach designed to improve system efficiency and stabilise how the storage interface works with the resonant converter. CP charging regulates the delivered power rather than maintaining a constant reflected impedance. For an ideal storage-side load, the equivalent resistance satisfies $R_{eq,dc} = V_{SC}^2 / P_{ch}$ and therefore still increases as the SC voltage rises. CP control can smooth the power trajectory and reduce abrupt power-command variations, but receiver-side impedance regulation remains necessary to decouple the resonant link from storage-voltage variation [153].

When the SC approaches its maximum allowable terminal voltage, constant-voltage (CV) charging can be used to prevent overvoltage and reduce the charging current near the end of the charging process [154]. Cell or module voltage balancing, when required, must be provided separately by passive or active balancing circuits.

In real WPT–supercapacitor systems, it is becoming common to use multi-stage charging profiles that combine CC, CP, and CV modes in sequence. These hybrid methods let designers take advantage of the supercapacitor's ability to accept high power at first, then move to safer and more efficient charging as the process continues [155].

Pulse charging should be distinguished from the multi-stage CC–CP–CV profiles described above. Low-frequency pulsed charging introduces alternating charging and relaxation intervals and has been investigated as a means of reducing capacity loss and delaying aging in lithium-based batteries [156]. However, this evidence primarily concerns battery charging rather than direct SC charging or complete WPT–SC systems.

For an SC interface, pulse or hybrid charging can modify the current and power trajectory, but it does not eliminate the underlying increase in SC terminal voltage or the associated variation in equivalent load

impedance. Poorly selected pulse amplitude, duty ratio, or repetition frequency may instead increase RMS current, DC-link ripple, converter loss, and thermal stress. Pulse-based operation must therefore be coordinated with the bandwidth and resonant dynamics of the WPT converter.

Variable-impedance control addresses the WPT-side problem more directly. An active rectifier or receiver-side DC/DC converter can regulate the effective impedance presented to the resonant link despite changes in SC voltage. This allows the resonant front-end to operate closer to its desired gain, current, and soft-switching conditions while the storage-side charging reference changes.

The two approaches are therefore complementary rather than interchangeable. A pulse or hybrid charging profile can define the desired storage-side current or power reference, while the controlled receiver interface shapes the impedance reflected to the WPT resonant network. Such coordination can mitigate battery-aging stress and wide-range SC charging effects, although it requires additional sensing, current limiting, and stability analysis.

Recent research highlights the need to connect charging control with higher-level energy management and resonance regulation [157]. In these integrated systems, the WPT converter is not just a power source but also helps manage how the storage interface behaves over time. Methods like adaptive resonance tracking, predictive current control, and digital impedance estimation have been tested to make the system more robust when loads or parameters change. This shows a move away from separate charging algorithms towards control strategies that consider the whole system and how its parts interact.

6.3. Energy management in WPT–hybrid systems

Battery–SC hybrid energy-storage systems exploit the complementary energy and power characteristics of the two storage devices. In frequency-based power-sharing strategies, the battery generally supplies the low-frequency or average power component, whereas the SC responds to rapid transients. Adaptive methods can further modify the power-split bandwidth according to the SC state of charge and operating condition [11,12].

In passive hybrid configurations, power sharing is governed mainly by the instantaneous voltages and internal impedances of the battery and SC. Although this architecture is simple, the absence of active decoupling limits controllability and may produce undesirable current distribution under dynamic conditions [9,139].

Using separate bidirectional DC/DC interfaces provides explicit control of the battery and SC power components. The SC can then absorb rapid power fluctuations while the battery follows a smoother reference, reducing battery-current stress and providing greater control over the storage-side impedance [12,142].

Table 9

Comparison of representative control strategies for WPT-storage systems.

Control strategy	Key principle	Relative dynamic response	Soft-switching	Load adaptability	Implementation cost	Typical application
Frequency modulation [111]	Detuning-based control	Medium	Limited under wide detuning	Moderate	Low	Low-power WPT, loosely coupled systems (IPT/CPT)
Phase-shift control [112]	Fundamental voltage control	Fast	Generally maintainable	High	Medium	Medium-power IPT systems, EV charging
Bilateral control [149]	Transmitter–receiver coordination	Fast	Strong with coordination	High	High	High-performance WPT, dynamic charging systems
MPC-based control [158,159]	Predictive optimisation strategy	Potentially fast	Constraint-dependent	High, constraint-dependent	Very high	Advanced WPT systems, multi-objective optimisation

Note: Dynamic-response descriptors are qualitative because the cited studies use different perturbations, sampling rates, controller bandwidths, settling criteria, coupling conditions, and hardware platforms. Reported response times and steady-state errors are therefore not directly comparable. Numerical values are included only when a common definition and operating condition are explicitly available.

Optimisation-based methods can provide additional coordination when multiple objectives and constraints must be considered. MPC has been investigated in WPT systems for adaptive power regulation and multi-objective optimisation, although computational burden and model dependence remain important implementation considerations [158,159].

For WPT-HESS applications, storage-side energy management should also be coordinated with resonant-link regulation. Receiver-side rectification and converter control can modify the impedance reflected to the WPT link, while electrothermal and aging information can be used to constrain the battery-SC power split [136,137]. The principal trade-offs among these control strategies are summarised in Table 9.

6.4. Safety, electrothermal, and aging-aware control

The increasing power level and charging rate of WPT-SC systems make electrothermal behaviour a system-level control issue rather than an independent component-design consideration. Thermal models used for supercapacitors can generally be divided into lumped-parameter and distributed models. Lumped one-node or multi-node RC thermal networks are computationally efficient and are therefore suitable for online temperature estimation and controller implementation. More detailed distributed models describe radial and axial temperature gradients within the cell and are more appropriate for offline design, parameter identification, and hot-spot analysis. Experimental studies on supercapacitors have validated transient thermal models under high-current charge–discharge operation and have demonstrated that internal temperature distribution cannot always be represented accurately by ambient or surface temperature alone [160].

The thermal behaviour of the WPT front-end must also be considered. In IPT systems, heat is generated by winding resistance, skin and proximity effects in Litz-wire coils, magnetic-core loss, eddy-current loss in shielding structures, and semiconductor conduction and switching losses. Thermal-circuit and finite-element models of WPT magnetic couplers have been experimentally validated on kilowatt-scale prototypes, showing that the transmitting and receiving coils can become the dominant hot-spot locations [77]. In CPT systems, dielectric loss, conductor loss, and high-frequency losses in compensation capacitors and rectifiers become increasingly important. Misalignment or coupling deterioration may further increase resonant current and reactive-power circulation when the controller attempts to maintain constant transferred power.

For the supercapacitor bank, the dominant irreversible heat source is commonly approximated by

$$P_{SC,loss} \approx I_{SC,rms}^2 R_{ESR}(T, V, \text{age}) \quad (10)$$

where the ESR depends on temperature, terminal voltage, frequency, and degradation state. Current ripple introduced by the rectifier and

DC/DC converter increases the RMS current without necessarily increasing the average charging power, thereby raising internal heat generation and accelerating degradation [56]. A thermal feedback mechanism can consequently develop: increased temperature changes the ESR and capacitance, which modifies the storage-side impedance and converter operating point; the resulting current redistribution may then produce additional loss and further temperature rise.

The WPT coils, rectifier, DC/DC converter, and SC bank may also be thermally coupled through a shared enclosure, cooling path, or local ambient environment. Heat generated in the resonant coupler and power electronic interface can raise the inlet or enclosure temperature experienced by the SC module, while inadequate spacing and cooling can produce unequal cell temperatures in series-connected SC banks. Such temperature gradients cause unequal ESR, voltage distribution, and aging rates, and therefore increase the burden on voltage-balancing circuits. Although experimentally validated thermal models exist separately for SC cells and WPT couplers, fully integrated electrothermal validation of complete WPT-SC charging systems remains limited. This represents an important research gap.

SC aging is governed by the combined influence of temperature, operating voltage, current ripple, and accumulated charge throughput. Calendar-aging models have demonstrated that elevated temperature and voltage accelerate capacitance reduction and ESR growth [131]. Aging-aware control should therefore not rely exclusively on instantaneous temperature limits. A more complete strategy can incorporate estimated core temperature, ESR growth, capacitance fade, voltage imbalance, and cumulative thermal exposure into charging-current and power-reference generation.

Practical protection should be implemented hierarchically. Fast hardware protection is required for overcurrent, overvoltage, loss of synchronisation, and abnormal resonant current. At the converter-control level, current limiting, temperature-dependent derating, soft-switching preservation, and DC-link protection can be coordinated with the inverter and receiver-side converter. At the energy management level, the charging current or battery-SC power split can be reduced when the estimated SC core temperature or aging index approaches its allowable limit. This layered architecture prevents intelligent or optimisation algorithms from overriding essential safety constraints.

6.5. Intelligent, predictive, and digitalised control trends

Intelligent control methods can support WPT-SC systems at different time scales, but their functions should be distinguished clearly. Neural networks are primarily suitable for nonlinear estimation and surrogate modelling, reinforcement learning is suitable for sequential decision-making and multi-objective optimisation, and digital twins provide continuously updated virtual representations for monitoring, prediction, and supervisory optimisation. These methods should not be treated as interchangeable control solutions, and their respective

Table 10
Comparison of intelligent control approaches for WPT–SC systems.

Approach	WPT–SC application	Capability	Control role	Main limitations
Neural-network estimation [161]	Estimate received power, coupling, or reflected impedance from transmitter-side measurements	Enables sensorless nonlinear estimation	Online estimation and feedforward compensation	Training-data dependence, poor extrapolation, and limited interpretability
AI-assisted adaptive control [162]	Tune controller parameters under coupling and load variations	Improves adaptation compared with fixed-gain control	Outer voltage or power loop	Requires representative data and stability verification
Reinforcement learning [163,164]	Coordinate phase shift, frequency, charging current, and power sharing	Supports multi-objective sequential optimisation	Supervisory energy management	Unsafe exploration, high training cost, and simulation-to-hardware mismatch
Digital twin [165]	Predict coupling, resonant behaviour, temperature, and aging	Supports monitoring and predictive optimisation	Supervisory optimisation and maintenance	Model synchronisation, sensor requirements, latency, and computational burden
Hybrid physics–data method	Combine physical models with learned parameters or residual errors	Improves generalisation with less training data	Multi-rate estimation and constrained optimisation	Greater modelling complexity and limited experimental validation

Note: Intelligent methods are generally more suitable for estimation and supervisory optimisation, while deterministic controllers retain responsibility for fast regulation and hardware protection.

applications, capabilities, control roles, and implementation limitations are summarised in Table 10.

A representative neural-network application is sensorless estimation of receiver-side WPT characteristics. Machine-learning models have been used to estimate the power delivered to the receiver from transmitter-side electrical measurements, reducing the need for receiver-side sensors and communication links [161]. In a WPT–SC system, a similar estimator could infer coupling condition, reflected impedance, received power, or impending efficiency degradation from transmitter voltage, current, phase angle, and operating frequency. The estimated variables could then be used to update the charging-current reference or receiver-side impedance command.

The principal limitation of neural-network estimation is its dependence on the training domain. A model trained using fixed coil geometry, temperature, compensation parameters, and SC voltage range may lose accuracy under unrepresented misalignment, component aging, or electromagnetic disturbance. Training-data coverage, model generalisation, sensor noise, uncertainty quantification, and online model updating must therefore be considered before such estimators are used in protection-critical control loops.

Reinforcement learning provides a different function. A potential WPT–SC application is online coordination of switching frequency, phase shift, receiver DC/DC duty ratio, and battery–SC power sharing. The agent state may include DC-link voltage error, SC voltage, estimated temperature, coupling condition, reflected impedance, and battery state of charge. The control action can be selected to minimise a reward function containing voltage deviation, converter loss, temperature rise, battery stress, and loss of soft switching. Reinforcement-learning approaches have demonstrated benefits in wireless-power scheduling and energy allocation problems, but direct experimental evidence for converter-level WPT–SC control remains limited [163,164].

The practical limitations of reinforcement learning are more severe than those of supervised estimation. Unsafe exploratory actions cannot be permitted in high-power resonant converters, and a policy trained in simulation may not remain stable when the real system contains unmodelled parasitic parameters, communication delay, saturation, or rapid coupling changes. Safe deployment therefore requires constrained action spaces, offline or digital-twin-based training, a verified fallback controller, and explicit current, voltage, temperature, and soft-switching limits.

Digital twins provide a system-level framework for combining these functions. Recent electromagnetic digital-twin research has used physics-guided deep learning to predict WPT behaviour in changing

industrial environments [165]. For a WPT–SC system, the virtual model could combine an electromagnetic coupling model, resonant converter model, SC electrothermal model, and aging estimator. Such a twin could predict the consequences of misalignment, cooling degradation, SC impedance change, or component aging before applying a new operating command to the physical system. It could also support predictive maintenance and lifetime-aware charging optimisation.

However, a useful digital twin requires continuous parameter synchronisation with the physical system. Its accuracy is limited by sensor availability, model-identification error, computational cost, communication latency, and the rate at which coupling and storage parameters change. A high-fidelity electromagnetic model cannot normally be solved at every switching period, while a highly simplified model may fail to predict important transient or thermal constraints. A multi-rate implementation is therefore more realistic: deterministic current, voltage, and resonant-control loops operate at the converter time scale, whereas neural estimation, reinforcement learning, and digital-twin optimisation operate as slower supervisory layers.

7. Research gaps and future directions

Despite significant advances in WPT systems integrated with supercapacitors and hybrid energy storage architectures, several fundamental challenges remain unresolved. Existing literature largely addresses individual components – resonant topologies, rectifiers, charging profiles, or energy management algorithms – in isolation. However, the next stage of development requires system-level integration, cross-layer optimisation, and robustness-oriented design. This section identifies key research gaps and outlines promising directions for future investigation.

In particular, emerging hybrid energy storage systems combining supercapacitors and batteries have highlighted the importance of co-ordinated power conversion architectures. When integrated with WPT front-ends, such converters can facilitate flexible power sharing between the battery and supercapacitor, enabling improved transient response and reduced battery stress. However, their performance remains sensitive to load variation and coupling conditions, indicating the need for unified co-design of converter topology, energy management, and wireless power transfer stages.

Table 11 summarises the key research challenges, future directions, and illustrative research entry points for WPT–supercapacitor systems. The proposed entry points translate the identified research gaps into specific modelling, control, and experimental tasks that may support future investigations.

Table 11

Summary of key research challenges, future directions, and illustrative research entry points in WPT–supercapacitor systems.

Research aspect	Key challenges	Future directions	Illustrative research entry points
Cross-layer co-design [166]	WPT front-end and storage control are commonly designed separately; SC dynamics modify the receiver-side equivalent impedance.	Unified co-design frameworks; integration of resonant tuning and storage control.	Develop a coupled small-signal model of the resonant link, rectifier, DC/DC converter, and SC; jointly optimise compensation parameters and controller gains over the complete SC voltage range.
Wide-range operation [167]	Wide load variation during SC charging; degradation of resonance, efficiency, and soft-switching conditions.	Predictive impedance shaping; model-based resonance tracking.	Estimate coupling and reflected impedance from transmitter-side voltage, current, and phase measurements; develop gain-scheduled control for different charging stages and misalignment conditions.
Multi-source coordination [12,145]	Coordination among PV, battery, SC, and WPT sources; multiple control timescales and complex power flows.	Distributed and hierarchical control; multi-source energy management.	Design a multi-rate strategy in which the SC supports rapid transients and the battery supplies average power; validate power sharing under SOC, voltage, current, and temperature constraints.
Lifetime and aging [131,142]	Limited integration of SC aging models into WPT control; capacitance reduction and ESR growth under intensive cycling.	Lifetime-aware optimisation; physics-informed aging models.	Estimate SC capacitance and ESR online from charging measurements; incorporate degradation cost into charging-current and power-sharing optimisation.
Thermal and safety [168]	Thermal coupling among the WPT link, converter, and SC bank; high-current operation and local hot spots.	Real-time thermal estimation; adaptive thermal management.	Develop a coupled electrothermal model of the WPT–SC system; experimentally validate temperature-dependent current derating under high-current charging and misalignment.
Standardisation [169]	Lack of unified testing and reporting procedures; compatibility and interoperability issues.	Interoperable architectures; standardised system frameworks.	Define benchmark profiles covering SC voltage, coupling, misalignment, temperature, and charging current; standardise reporting of efficiency, transient response, EMI, and thermal stress.
Intelligent control [170]	Limited generalisation of data-driven methods; stability, safety, and interpretability concerns.	AI-based control strategies; hybrid model-driven/data-driven methods.	Develop physics-informed estimators for coupling, SC temperature, and aging state; evaluate reinforcement learning or digital-twin optimisation as a constrained supervisory layer.
System integration [16,23]	WPT is frequently treated as an isolated converter; limited system-level and multi-objective optimisation.	Integration into broader energy ecosystems; multi-objective system optimisation.	Construct an integrated prototype containing the resonant link, rectifier, DC/DC interface, sensing, and SC storage; validate it under simultaneous coupling, load, temperature, and SC-voltage variations.

Note: The listed research entry points are illustrative rather than prescriptive. Their implementation depends on the selected IPT or CPT architecture, operating frequency, power level, storage configuration, and intended application.

8. Conclusion

This review has examined WPT-enabled supercapacitor and hybrid energy storage systems from a system-level integration perspective. The analysis shows that the key challenge in such systems is not only efficient contactless power transfer, but also the dynamic interaction between resonant WPT front-ends and time-varying storage loads. Because supercapacitors exhibit continuously varying voltage, capacitance, ESR, and equivalent impedance during charging, they can alter the reflected load seen by the resonant network, resulting in resonance detuning, reduced soft-switching margin, and efficiency degradation.

The reviewed literature indicates that power conversion interfaces, compensation networks, rectifier structures, DC/DC converters, and hybrid storage configurations must be co-designed rather than treated as isolated subsystems. In particular, receiver-side regulation, active rectification, bidirectional DC/DC interfaces, and hybrid battery–supercapacitor architectures can provide effective load-shaping capability and improve system robustness under dynamic charging conditions.

Control and energy management strategies are therefore central to future WPT–supercapacitor systems. Conventional frequency modulation and constant-current charging remain useful for simple systems, but they may be insufficient under wide-range load variation. More advanced methods, including phase-shift control, bilateral control, model predictive control, adaptive impedance estimation, and AI-assisted optimisation, offer promising routes towards stable, efficient, and lifetime-aware operation.

Future research should focus on cross-layer co-design of WPT and energy storage interfaces, predictive impedance shaping, electrothermal and aging-aware control, and experimentally validated architectures for practical high-power applications. Overall, WPT-enabled supercapacitor and hybrid energy storage systems represent a promising direction for fast, flexible, and robust energy storage integration in transportation, robotics, distributed energy, and industrial applications.

CRedit authorship contribution statement

Zhixing Liu: Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation, Formal analysis, Conceptualization. **Sadeeshvara Silva Thotabaddadurage:** Writing – review & editing, Supervision, Project administration. **Tek Tjing Lie:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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