

Review of Key Technologies and Optimization Methods of Vehicle Dynamic Wireless Charging Systems

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Abstract: *The new energy vehicle market is exploding, but two big issues keep dragging it down: limited driving range and clunky charging setups. For starters, wired charging? It's just asking people to plug and unplug cords manually, which gets old fast. The connectors themselves wear out, especially in bad weather. Rain or snow can mean leaks—a real headache. Battery swapping stations sound promising, but they're expensive to build and keep running. Plus, carmakers insist on their own battery specs, so scaling up just isn't happening. Dynamic wireless power transmission (DWPT) flips the script. Cars can charge as they drive, making range anxiety less of a thing—exactly what autonomous vehicles and smart transport need. DWPT stands out as the next big step in charging technology. Researchers everywhere dive deep into coil design, resonant circuits, and performance optimization. Still, the field hasn't figured everything out. The way coupling mechanisms and compensation topologies match specific situations is unclear. Charging a bunch of vehicles at once strains the power grid. Changes in vehicle speed, coil placement, and device parameters don't have a unified framework, and no one's nailed a full theory for optimizing lots of factors together. Most reviews get stuck on hardware, ignoring how magnetic fields, circuit design, and control logic actually work together. This leaves gaps—anyone trying to boost simulations or algorithms ends up missing key pieces. This article zooms in on segmented guide rail systems with vehicles carrying multiple pickup coils. It unpacks three major components: magnetic coupling mechanisms, resonance compensation circuits, and dynamic balance controls. The article compares the main technical solutions being used in China and other countries—how they perform, what they cost, and whether they play nice with household EVs. It lays out the standards that need attention and builds a multi-dimensional system to evaluate everything. The analysis looks into where household EVs fit, shows the direction for tech upgrades, and sketches out the path to full-scale commercialization. All of this strengthens the theory behind segmented-multi-pickup composite charging, highlights areas needing more research, and gives engineers and researchers a clear reference for real-world progress and innovation.*

Keywords: Dynamic wireless power transmission; Segmented guide rails; Multi-pickup coils; Resonant topology; Dynamic anti-interference control; New energy vehicles.

1. INTRODUCTION

1.1 Research Background and Significance

1.1.1 Industry application background

The domestic new energy vehicle market is currently experiencing a remarkable surge in growth, yet the less-than-ideal charging experience continues to pose a significant hurdle to achieving broader market acceptance. Traditional wired charging methods, while widely used, are marred by several drawbacks, including cumbersome operational procedures, accelerated interface wear, and potential safety risks under extreme environmental conditions. On the other hand, while battery swapping stations offer a promising alternative, they too encounter substantial challenges, such as exorbitant initial investment costs and restricted battery compatibility, which collectively impede their widespread implementation.

Dynamic wireless charging presents a revolutionary approach by removing the necessity for physical contact between charging systems and vehicles, thereby allowing vehicles to recharge effortlessly as they move. This innovation not only diminishes the reliance on large-capacity batteries but also contributes to reducing the overall weight of vehicles and subsequently lowers manufacturing expenses. Particularly well-suited for short commutes in parks, urban travel, and highway driving, dynamic wireless charging emerges as an essential energy replenishment strategy within the framework of intelligent transportation systems.

1.1.2 Significance of theoretical research

Universities and companies—both in China and around the world—keep cranking out new coil structures,

compensation circuits, and all sorts of segmented control strategies. The problem? Everyone's working in isolation. Nobody can agree on a single way to measure or compare performance. So, you see familiar coil structures like DLDD, DDQ, and BPP getting tested, but never pitted directly against each other. Researchers publish results one by one. They rarely pull everything together to show where each approach actually fits best. Now, if you dig into how SS, LCC, and other resonant circuits manage voltage and power stability during segmented dynamic charging, you notice there's no complete picture. Results come scattered—bits here, bits there. You never really see a comparison that helps anyone figure out which method wins in practice. Look at mutual inductance fluctuation. Think vehicle speed changes or coil misalignment—there's almost no systematic review out there. It's even worse when you factor in how different control algorithms react, especially with hardware costs and real application requirements on the table. The whole scene feels fragmented and chaotic.

While current reviews predominantly focus on static single-coil configurations or long guide rail systems with single receiving coils for charging purposes, there has been a notable lack of attention toward the innovative "segmented guide rail combined with multi-pickup coil" composite setup. This particular design stands out due to its exceptional resistance to offset issues and remarkably low no-load loss, characteristics that make it especially well-suited for residential electric vehicle applications. Despite these advantages, however, a thorough and structured research framework that systematically explores its technical intricacies, advantages, drawbacks, and inherent limitations is still notably absent.

This article presents a meticulous synthesis of existing research, offering an in-depth exploration of the operational principles and essential conditions underpinning a wide array of technologies. By thoughtfully evaluating the strengths and limitations of various solutions, it not only addresses the prevalent issues of research fragmentation and the lack of comparative studies but also establishes a robust, all-encompassing theoretical framework. This framework, in turn, serves as a valuable guide for advancing both hardware and algorithm development in the future.

1.1.3 Significance of engineering industry

This article doesn't just stack up numbers—it puts domestic and international pilot projects side by side to compare everything: road reconstruction costs, what it takes to modify vehicles, and the ongoing expenses to actually run and maintain different technical setups. You get the full picture, not just a list. It digs into what's slowing down wider adoption, naming the big barriers up front. Then it rolls out a detailed evaluation system. Think of it as a toolkit for decision makers: you get metrics on power transmission efficiency, anti-offset capability, construction costs, lightness, and electromagnetic safety. No single angle here. Car brands and infrastructure developers get clear standards to help them choose the right solution. And the article connects these criteria to real-world rules—current power grid dispatch policies and industry standards—so it shows exactly where each tech fits best. The result? It sketches out how dynamic wireless charging can finally get moving outside the lab, and become part of day-to-day projects.

1.2 Research Status at Home and Abroad

1.2.1 Domestic research status

In the realm of domestic research, dynamic wireless charging technology has primarily focused its attention on enhancing the charging capabilities of household electric vehicles (EVs). Researchers are delving into innovative multi-coil array configurations to optimize charging efficiency, refining lightweight magnetic core designs to improve portability and reduce energy loss, and ensuring driving power remains stable throughout the charging process. Notably, institutions such as Chongqing University, Hunan University, Southwest Jiaotong University, and the Harbin Institute of Technology have emerged as pivotal contributors, driving advancements in this promising field.

Chongqing University's DLDD double-layer double-D coil takes the old DD coil design and cranks it up. The team didn't just tweak the magnetic circuit—they stretched the lateral anti-offset range by 40%. That's not minor. Power fluctuations show up when vehicles move across segmented guide rails, but with LCC compensation topology, charging stays efficient even if the coil's way off-center. They didn't settle there. The engineers came up with a multi-coil decoupling design. That cuts down magnetic field interference between branches and keeps the system steady. This isn't just lab theory either; the team patented their tech and tested it out on commercial commuter vehicles. Meanwhile, Hunan University's researchers put together a multi-receiving coil system using

forward and reverse series connections. By adjusting magnetic field offsets, they prevent mutual inductance from shooting up when coils shift — and keep overall fluctuations nailed down at 3%. On top of that, they built a rectangular coil mutual inductance calculation model, so simulation runs quicker and circuit designers now have solid theory to choose topologies for multi-coil setups. Southwest Jiaotong University pushes into the heavy-duty zone — high-power wireless charging for trucks and rail systems. Their design uses multi-transmit and multi-receive decoupling, wiping out interference between magnetic channels and pumping out a steady 200kW in actual conditions. They built a strong equivalent model to deal with parameter offsets and rolled out model predictive control to squash power swings and stop efficiency loss. Plus, they compared wireless power supply schemes based on magnetic and electric fields, giving solid reference points for anyone who wants to streamline small vehicle designs.

Lu Yuanfang's team didn't just stop at the basics with the SS-type compensation circuit. They got hands-on, building a model that actually tracks how coil parameters shift while the system runs. Once they had that, they unleashed a particle swarm algorithm offline to find the best capacitor values. The result? The system chews through a lot less computing power when it's working in real time [8]. Over at Harbin Institute of Technology, researchers in 2024 whipped up a fresh take on the segmented BPP transmitting coil. They built in decoupling capacitors right into each segment to wipe out interference, and layered on segmented switch control for good measure. This smart combo finally tackled a persistent problem: that annoying dip in power when vehicles rolled past gaps in the guide rail [7]. Then there's Ye Xing and the team in 2023. They didn't mess around—they went with a segmented BPP launch track, a double-layer DDQ receiving coil, and added LCC-LCC compensation topology to both sides. The standout? They nailed down segment-by-segment power supply switching with no external position sensor needed. And their double-layer coil design? It smoothed out offset power drops by letting one layer pick up the slack for the other [17].

Right now, ZTE New Energy and BYD have electric bus prototypes on the road, testing routes in the park. It's progress, no doubt. But domestic research still lags in some obvious ways. Teams are spread out, working on their own projects, so the results turn out scattered—a bit chaotic, honestly. Nobody follows the same standards to measure how well their designs work, which makes comparing technical solutions a headache. Plus, everyone zeroes in on just one piece of the puzzle, like bumping up efficiency or anti-offset performance, and skips over important factors—cost, electromagnetic compatibility, reliability, all crucial but often ignored. And let's not forget, there's barely any in-depth review of segmented multi-pickup composite architecture. Without that kind of overview, digging into the details of those specialized systems is nearly impossible.

1.2.2 Current status of foreign research

Foreign researchers embarked on the exploration of dynamic wireless charging technology at an earlier stage, which has enabled them to cultivate highly sophisticated theories concerning electromagnetic fields and resonant circuits. As a result, they now possess a distinct advantage in understanding fundamental mechanisms, conducting large-scale engineering tests, and advancing standardization efforts. Among the leading institutions driving progress in this field are the University of Auckland in New Zealand, KAIST, Oak Ridge National Laboratory, and Siemens, each contributing unique expertise and innovation.

The Auckland University team really shook up coil and circuit theory with the DD coil. By focusing on the steep drop-off in mutual inductance when a circular coil slips out of alignment, they found a way to keep performance steady. That idea pretty much laid the groundwork for static and dynamic wireless charging coils we use today. Then they went further—DDQ quadrature coils stepped up anti-offset performance, no matter the direction. They didn't stop at hardware, either. The team mapped out the equivalent circuits and output characteristics for SS, SP, and LCC topologies, and came up with a universal approach to matching parameters in wireless power transfer systems. Across the water in Korea, the Academy of Science and Technology took their own path. They released the OLEV dynamic charging system and kept refining the long rail launch structure, looking to even out the magnetic field along roads. Their researchers were the first to explore segmented coil timing switching, which cuts power distortion as vehicles zip along. With those changes, rail-type dynamic wireless charging started making its way into actual engineering projects. Back in the US at Oak Ridge National Laboratory, high-power coupling systems got most of the attention. Engineers there built multi-phase coil prototypes, rated for hundreds of kilowatts. That brought its own headaches—think magnetic core saturation and efficiency nosediving at high power. Their fix? A single-stage AC-AC direct conversion topology that trims power conversion losses. It's just what you need for big jobs, like trucks or railway applications. Then there's Siemens in Germany, who dove in with the eHighway freight line. Their extended guide rail system pumps up to 700kW—plus the system's efficiency stays above 90%.

But you pay a lot for that kind of power. It's great for freight lines that are closed off, but if you're talking about everyday family cars? Not really practical.

Most foreign coil designs do their job on long, straight guide rails, where trains cruise along at a steady speed. But once you get into systems with a lot of switches, segmented rails, or unpredictable power demands—especially in passenger cars—those same designs start to struggle. The theory behind multi-receiving arrays hasn't caught up yet either. Simulation models tend to breeze past real-world headaches like shifting speeds or when a train isn't perfectly aligned. And no one's come up with a joint, multi-objective optimization framework that tackles these messier problems. Nearly all the reviews you find focus on a single coil or a simple topology. They rarely dive into how complex, multi-receiver composite structures actually perform, what their strengths or weaknesses are, or where they really fit best.

1.2.3 Comparative summary of domestic and foreign research

Research done in other countries mostly focuses on basic theories and is especially good at creating models for high-power, single-coil steady-state systems designed for heavy freight trains. On the other hand, China starts with existing theories and pays more attention to multi-coil systems to better fit the needs of busy urban areas and electric vehicles used by households.

Each country has its own weaknesses in this area. Foreign research doesn't have a complete theory on how multiple coils couple together, and their simulation models are too simplistic, ignoring real-world disturbances that happen while driving. In China, there isn't enough basic theory for systems over 200kW, research standards differ between teams, and control algorithms that are lightweight and require low computing power still need improvement.

This article takes a close look at the segmented guide rail with a multi-pickup coil composite system. It carefully studies five important technologies: how the parts connect (coupling mechanisms), different resonant designs (resonant topologies), controlling the system while it's moving (dynamic control), handling large amounts of power (high-power conversion), and avoiding interference between electrical parts (electromagnetic compatibility). The article compares solutions from home and abroad, explains when to use each approach, and offers ways to improve them.

1.3 Overall Structure of the Article

This article moves through six chapters, each building on the last. Chapter 1 lays out the groundwork: it explains the research background, why this topic actually matters, and where the field sits right now—both in China and internationally. It highlights what's missing in earlier studies and spells out the problems this article addresses. Chapter 2 unpacks the segmented-multi-pickup composite charging system. Here, you'll see how the entire system operates, with every component and mechanism getting some spotlight. By Chapter 3, the discussion sharpens—it's all about the core technologies. The text traces the development and performance of main coil types, resonant circuits, and control strategies. Then comes Chapter 4, which lines up three top dynamic wireless charging solutions for a direct comparison, breaking down not just how they differ, but where each one actually makes sense to use. Chapter 5 faces the tougher reality: the big obstacles that block these technologies from industry-wide rollout. It doesn't just talk in general terms; it introduces a quantitative framework to evaluate these challenges from several perspectives. The final chapter steps back, surveys the broader trends in the technology, looks at where industrialization could go, and wraps up with a tight summary of the main insights.

2. BASIC ARCHITECTURE AND PRINCIPLES OF SEGMENTED-MULTI-PICKUP COMPOSITE CHARGING SYSTEM

2.1 Overall Composition of the System

The entire system is divided into two parts: road transmitting and vehicle receiving, and is matched with a background collaborative control platform [12].

The road surface system is ingeniously designed with a comprehensive array of components, including a power grid input unit that serves as the initial gateway for electrical energy, a high-frequency inverter to efficiently convert and regulate this power, a segmented transmitting coil track that strategically distributes the energy along

the roadway, and segmented switching switches that enable precise control over the energy flow. Meanwhile, the vehicle itself is outfitted with a sophisticated setup comprising multiple pickup coils to capture the transmitted energy, resonance compensation circuits to ensure optimal power transfer, rectifier and voltage stabilizing modules to maintain a steady and usable electrical output, and a power battery management system to oversee the storage and utilization of this energy. Complementing this intricate hardware is a supporting control unit, which diligently collects real-time data such as vehicle speed and battery power levels, and then leverages this information to automatically manage the power supply segments, fine-tune impedance for enhanced efficiency, and balance the outputs across various branches, thereby ensuring a seamless and optimized charging experience.

When the vehicle rolls over the powered guide rail, the transmitting coil throws out an alternating magnetic field. Pickup coils on the vehicle pull in that energy—thanks to electromagnetic induction. Next, a compensation circuit jumps in, lining up the impedance and pushing the energy transfer to work better. The system flips the current into DC, so the battery gets charged. As the vehicle leaves one section behind, the controller kills power to that rail and lights up the next. Several pickup coils pitch in; they cover any gaps between rail segments, so charging doesn't hiccup. This setup cuts down power loss and keeps the charging smooth—no interruptions, even while the vehicle's cruising.

2.2 Basic Principles of Magnetic Field Coupling

The system operates by harnessing alternating magnetic fields to facilitate energy transfer, with its overall transmission capacity resting squarely on the mutual inductance established between the transmitting and receiving coils. This mutual inductance, in turn, is shaped by a range of factors, including the size and positioning of the coils, the air gap separating them, and the material used for the core.

In traditional circular coil systems, even minor deviations in alignment can trigger a significant drop in mutual inductance, which in turn drastically reduces charging efficiency—a critical challenge for seamless wireless power transfer. Multi-coil arrays address this limitation by strategically distributing coils; when misalignment occurs, at least one coil group remains optimally coupled, thereby expanding the system's operational range and ensuring consistent performance across varied positioning scenarios. Complementing this, segmented guide rails enhance efficiency by activating only the section directly beneath the vehicle, effectively curbing unnecessary magnetic field dissipation during idle intervals and alleviating strain on the grid by reducing reactive power requirements. Together, these innovations create a more resilient, adaptive, and energy-conscious charging infrastructure.

Multi-layer composite core coils, such as DD, DDQ, and DLDD variants, are engineered to elevate the coupling coefficient by employing a stacked magnetic circuit design. This strategic layering not only concentrates the magnetic flux for improved efficiency but also effectively confines the magnetic field, thereby minimizing external electromagnetic interference. Nevertheless, a challenge arises when deploying multiple receiving coils in close proximity, as their mutual interactions can induce unwanted resonance shifts and erratic power fluctuations. To mitigate these issues, engineers have developed several practical solutions: integrating reverse-series coil configurations to counteract inductive coupling, adopting staggered spatial arrangements to reduce cross-talk, and incorporating decoupling capacitors to stabilize the system by filtering out parasitic oscillations. These approaches collectively ensure reliable performance in high-density wireless power transfer applications.

2.3 Working Principle of Resonance Compensation Circuit

When a coil is connected directly to a power circuit, its natural inductance and extra resistance cause it to generate a lot of reactive power, which makes the transmission of electricity less efficient. A resonant compensation circuit uses matching capacitors and inductors to balance the impedance, reducing energy losses and keeping the output stable.

SS, SP, PS, and PP topologies do a fine job when you want something straightforward and affordable. The catch? They don't cope well when mutual inductance shifts. Their output turns shaky—so if you're picturing dynamic, real-time charging while a vehicle's in motion, think again. These setups only come through for stationary, fixed-point charging, like cars parked in a garage. LCC high-order topology is different. It thrives where the others stumble. Thanks to multi-stage component optimization, it holds the output steady, manages soft switching no matter the load, and trims energy losses along the way. That's why engineers pick it for prototypes that need to charge vehicles on the move. Reconfigurable topology pushes adaptability even further. It can alter its own circuit structure on the fly, tuning itself in real time as mutual inductance shifts. That makes it king when you need to

handle changing conditions. But nothing's perfect—the control logic gets complicated, fast. For now, this approach is stuck in the lab, not ready for commercial rollout just yet.

2.4 Basic Logic of Dynamic Control

When a vehicle is moving, its speed, the position of its coil, and the amount of power in its battery keep changing, which causes the system's operating point to shift. Because of this, the closed-loop controller has to make real-time adjustments, and it mainly focuses on three main control goals.

Here's a refined, professional rendition of your paragraph with enhanced flow and stylistic variety: Segmented guide rail switching control optimizes energy efficiency by leveraging mutual inductance for precise vehicle position detection, ensuring power is supplied solely to occupied track sections to eliminate no-load energy waste. This system requires rapid, millisecond-level responsiveness to execute seamless power transitions during operation. Furthermore, its sensorless identification approach removes the need for road-mounted hardware, significantly reducing infrastructure costs and enhancing suitability for deployment on urban public roads. This version maintains technical accuracy while improving readability through varied sentence structures, strategic transitions like **furthermore**, and a cohesive narrative flow.

In addressing the challenges posed by coil coupling disparities within array systems, multi-pickup branch power balance control emerges as a pivotal solution. Given the diverse and often unpredictable operational conditions these systems encounter, the risk of single-branch overload becomes a significant concern, potentially compromising both efficiency and reliability. To mitigate this issue, a strategic approach involves fine-tuning the output impedance of each branch, thereby ensuring a harmonious distribution of current across all channels and enhancing overall system stability.

Disturbance suppression algorithms play a crucial role in mitigating the challenges posed by sudden mutual inductance jumps, which often arise from abrupt shifts in vehicle speed or substantial displacements of the coils. Among these methods, model predictive control stands out as a particularly effective strategy; it leverages real-time data on vehicle speed and positional offsets to anticipate the system's future state, thereby enabling preemptive adjustments to the circuit that facilitate swift and precise responses. On the other hand, adaptive PID control offers a distinct advantage by dynamically adjusting to significant parameter variations without requiring an exact model of the system, although this flexibility comes at the cost of placing greater computational demands on the on-board controller.

3. SORTING OUT THE CORE KEY TECHNOLOGIES OF COMPOSITE SYSTEMS

3.1 Magnetic Coupling Coil Technology

Dynamic electroless coils exhibit a diverse array of structural configurations, ranging from elongated guide rails employed at the transmitting end to multi-pickup array coils utilized at the receiving end. In this discussion, we will focus specifically on the segmented transmitting combined with multi-pickup receiving arrangement tailored for household vehicles, delving into its primary coil types and analyzing the distinctive performance characteristics that define this setup.

There are two primary types of basic planar coils: circular and DD coils. Circular coils are easy to make and cost-effective, yet they

Moving on to the second aspect, multi-layer orthogonal composite coils are exemplified by DLDD and DDQ coils. The DLDD coil stands out due to its construction, which involves the superposition of double-layer magnetic circuits. This unique design not only enhances its lateral anti-offset range by a significant 40% but also ensures a higher coupling coefficient, as evidenced by reference [15]. On the other hand, the DDQ coil features vertical orthogonal windings, a configuration that enables it to seamlessly adapt to both horizontal and vertical offset working conditions. While both types of coils boast minimal magnetic field leakage and high electromagnetic safety, they do come with certain trade-offs. Specifically, their larger size and weight mean they will occupy more installation space within the chassis, as noted in reference [4].

Third, there's a segmented BPP transmitting coil. The coils are placed in sections along the driving direction, and each section is the right length for a household car. The power turns off automatically when no cars are going by,

so there's hardly any energy wasted when it's not in use. By adding extra coils at right angles, the magnetic field on the road is more even, which helps fix the issue of power dropping in the gaps between sections and makes it work well for slow driving in cities.

Fourth, there are forward and reverse series multi-pickup array coils. Several sets of DD/DDQ coils are placed vertically and horizontally on the vehicle chassis. The magnetic field changes caused by misalignment are balanced out by connecting the coil windings in forward and reverse series. This keeps the overall mutual inductance fluctuation under 3%, greatly improving the stability of driving and charging. However, the main problem with this setup is cross magnetic field interference from multiple Louis branches, so a special decoupling structure design is needed.

Summary of advantages and disadvantages of various types of coils:

For a long guide rail launch, the circuit is simple and easy to control, but the whole system stays powered on, leading to large no-load losses that put extra strain on the power grid [6]. For a segmented launch rail, no-load losses are low, and it can be powered section by section at different times, but it needs extra switches and position sensors, making the hardware more expensive [12]. A single receiving coil is small and easy to control, but it can only handle a limited amount of misalignment.

Multi-pickup array: strong anti-offset capability and stable driving power, but coil wiring and power balance control are more complex [10].

Multi-layer composite coil: high coupling efficiency and less magnetic field leakage, but the manufacturing cost and vehicle weight are higher than ordinary planar coils [4].

3.2 Resonance Compensation Circuit Technology

In accordance with the sequential progression of technological advancements, the resonant compensation circuit can be categorized into four primary topologies: the foundational four-level topology, the sophisticated LCC high-order topology, the parameter optimization-enhanced topology, and the dynamic reconfigurable topology. As we delve into the specifics, let's explore how each of these circuit types adapts to various working conditions.

The fundamental topologies of SS, SP, PS, and PP configurations are characterized by their simplicity, featuring a minimal number of components and offering a cost-effective solution. These setups are capable of achieving highly efficient soft switching, provided that the coupling conditions remain constant. Nevertheless, their performance suffers significantly when it comes to output stability, as even slight fluctuations in mutual inductance can lead to considerable instability. Consequently, these topologies are primarily suited for static parking space charging scenarios, where conditions are predictable and stable, but they fall short when it comes to dynamic driving energy replenishment, where variable conditions demand greater robustness and adaptability [19].

The bilateral LCC symmetric topology stands out as it incorporates LCC compensation networks at both the transmitting and receiving ends, endowing it with the advantageous characteristics of constant current input and constant voltage output. Notably, it demonstrates remarkable stability, exhibiting minimal power fluctuation even under significant offset conditions, and maintains low losses across the entire load range. These attributes collectively make it the go-to solution for current dynamic charging commercial prototypes, as evidenced by its widespread adoption in the field [17]. However, it's not without its drawbacks; the topology necessitates a large number of components, contributing to a higher volume and cost at the vehicle terminal. Additionally, the multi-coil system demands an independent branch circuit configuration, further complicating the overall hardware setup and increasing its complexity [25].

Parameter optimization and better SS topology use offline algorithms to make the compensation capacitance parameters work better. During the time when the equipment is running, there's no need for real-time frequency modulation or phase shifting. This cuts down a lot on the controller's power use for computing and is a big plus for lightweight hardware [8]. But, when there are large offsets, the voltage stabilization isn't that great, so it's only good for low-speed and small-offset situations in closed parking areas [8].

The reconfigurable system that can change its circuit setup using semiconductor switches can adjust itself to match real-time mutual inductance values as needed, making it highly adaptable under all operating conditions. However,

the logic needed to drive the multi-channel switches is complicated, the hardware and control systems are expensive, and there are no large-scale commercial applications of this technology yet.

Summary of circuit scene adaptation

When considering urban arterial roads and situations involving significant vehicle offsets, the bilateral LCC-LCC topology emerges as the preferred choice, as highlighted in reference [17]. For closed campuses where cost efficiency is a primary concern, the improved and optimized SS topology offers a viable solution, as discussed in reference [8]. In demonstration projects that prioritize achieving the highest level of dynamic adaptation performance, opting for a reconfigurable topology is advisable, as suggested in reference [23]. However, it's important to note that the basic four-level topology is primarily designed for static fixed-point charging scenarios and does not cater well to vehicle driving charging needs, as outlined in reference [18].

3.3 Segmented Switch and Equalization Control Strategy

When it comes to managing driving conditions, the primary focus lies in addressing three critical aspects: optimizing the energy-efficient switching of segmented guide rails, achieving power equilibrium across multiple pick-up branches, and effectively mitigating power fluctuations that arise due to variations in vehicle speed and offset.

Segmented guide rail timing switching control takes its cue from South Korea's OLEV system. The principle is simple: by reading mutual inductance, the system tracks the vehicle's position in real time. Only the section of the guide rail under the car connects to the inverter, while the rest stays off—no wasted energy, no idle magnetic fields. That's efficiency. This segmented switching needs to react in milliseconds. Thanks to multiple pickup coils working together, the system manages to keep power steady, even as the vehicle crosses gaps. Crucially, sensorless mutual inductance identification does away with extra sensors in the road. That keeps infrastructure costs down and makes the whole setup ideal for busy city streets.

For multi-pickup branch power balance control, since each branch in the array has a different coupling strength, it's easy for a single channel to overload and damage the device. There are two common ways to solve this. One is independent DC-DC voltage regulation and equalization control, which is very accurate but requires more hardware. The other is a primary-side collaborative impedance adjustment circuit, which is simple but has a limited range for equalization adjustment.

4. MULTI-DIMENSIONAL COMPARISON OF GLOBAL MAINSTREAM DYNAMIC WIRELESS CHARGING ROUTES

Currently, the industry has established three well-developed technology routes: firstly, foreign solutions that utilize long guide rails for single-pickup operations; secondly, domestic approaches that feature park-static multi-pickup arrays; and thirdly, composite architectures that combine segmented guide rails with multi-pickup systems [21]. Each of these three routes exhibits distinct design philosophies, performance traits, and suitable application scenarios, highlighting their unique contributions to the field.

4.1 Design Ideas for Three Types of Routes

To begin with, when considering foreign implementations of long guide rail single pick-up routes, two prominent examples stand out: Siemens eHighway and the first-generation OLEV system. These routes are characterized by their continuous long launch rails embedded in the road surface, while the vehicles traversing them are outfitted with a single high-power coil setup. The primary focus of research and development in this domain revolves around delivering high-power electricity to heavy-duty freight vehicles and rail transit systems. In this pursuit, ensuring robust transmission power and efficiency takes precedence, often overshadowing concerns about no-load losses and construction expenses. However, it's important to note that this technology finds its niche primarily in closed freight corridors and is not deemed suitable for widespread adoption in household passenger vehicles.

Next, let's consider the implementation of static multi-pickup array routes within domestic campus environments. In this approach, a short-distance fixed charging segment is strategically placed along the roadway, allowing vehicles to drive slowly into the designated spot for charging. To enhance the system's resilience against excursion, multi-pickup coils are incorporated. This particular solution stands out for its relatively low investment in

infrastructure modification and straightforward implementation process. Nevertheless, it's important to note that this method is limited to providing energy replenishment solely at fixed points, lacking the capability to support charging while the vehicle is in motion across all road sections. Consequently, the applicability of this scenario is significantly constrained.

Thirdly, the segmented guide rail combined with a multi-pickup composite architecture stands as the predominant technical approach tailored for family passenger cars. By amalgamating the strengths of the two preceding solutions, this architecture enables energy-efficient power supply across the entire road section through the use of segmented guide rails. It leverages multi-pickup coils to enhance adaptability to various working conditions, striking a balance between performance, cost-effectiveness, and versatility. Consequently, it holds the greatest potential for widespread civilian application.

4.2 Comprehensive Indicator Comparison Table

Technical route	Charging power	peak efficiency	Resistance to deflection	road infrastructure costs	Vehicle installation cost	Adaptation scene	Core shortcomings
Long guide rail single pickup(foreign)	200~700 kW	>90%	weak	extremely high	medium	Freight dedicated lines、Rail transit	Large no-load loss、High cost, not suitable for small family cars [21]
Static multi-pickup array (domestic campus)	30~80kW	85%~89%	Strong	low	On the high side	Low-speed commuting in closed parks	Only charging at fixed points, unable to replenish energy while driving on the entire road section [5]
Segmented multi-pick composite architecture	30~150kW	86%~90%	Extremely strong	medium	On the high side	Urban roads, high-speed household passenger cars	Multi-branch control logic is complex and lacks unified industry evaluation standards [4]

4.3 Sources of Route Differences

Early on, overseas markets pushed dynamic wireless charging mainly for heavy-duty freight. They zeroed in on high-power, long-guide rail systems that could deliver steady energy for these big vehicles—nobody spent much time thinking about the lower-cost, all-road charging that family cars need. In China, things look different. Household passenger cars dominate the new energy vehicle scene, and city roads get messy fast. Drivers here care a lot about cost, so local research leans into multi-coil anti-offset designs, segmented power supply, and lightweight solutions. Still, China trails other countries when it comes to the core theory behind high-power systems and building unified industry standards.

5. DIFFICULTIES IN INDUSTRIALIZATION IMPLEMENTATION OF COMPOSITE SYSTEMS AND MULTI-DIMENSIONAL EVALUATION CRITERIA

5.1 Multi-level Problems of Industrialization

5.1.1 Technical Difficulties

Most ways to block magnetic interference between coil branches end up making the coils bigger and the hardware more complicated. So, you can't easily get both strong interference protection and a lightweight design. Usually, people focus on just one thing: improving efficiency or fighting offsets—rarely both. It's uncommon to find a solution that tackles transmission efficiency, magnetic leakage, size, and controller power all at once. When you boost charging power, the converter and coil inevitably get larger and heavier, and that's a real headache if you're trying to squeeze everything into the tight chassis of a typical car.

5.1.2 Problems in project implementation

Laying guide rails in separate sections, buying magnetic cores, and running underground wiring all cost quite a bit. Rebuilding city roads on a big scale? That strains local budgets. Then there's the headache of different car

manufacturers using all sorts of chassis setups and battery specs. Multi-pickup coils don't fit well across the board, so there's no easy install that works for everyone. Now, when lots of electric vehicles charge on the go at the same time, the power load spikes in one spot. During peak hours, residents see even more pressure on the grid. That makes voltage regulation harder and forces utilities to boost capacity just to keep up. The answer? Cities need a coordinated way for vehicles, roads, and the power network to work together. Otherwise, grid management just gets more difficult.

5.1.3 Industry standard problems

Currently, there isn't a single, globally agreed-upon size for dynamic wireless charging coils, a standard test specification for their topology, or a unified segmented switching communication protocol. Different companies and labs use different test conditions and evaluation criteria, making it hard to fairly compare different technical approaches. Also, regulations concerning the safety of magnetic field radiation from dynamic charging and vehicle electrical safety are still being developed, which holds back the widespread launch of these products in the market.

5.2 Multi-dimensional Quantitative Evaluation Criteria for Segmented Multi-pickup Composite Systems

Addressing the industry's pressing need for a standardized evaluation framework, this article introduces a meticulously designed five-dimensional quantitative standard that enables an objective and comprehensive comparison of diverse coil designs, topological architectures, and control strategies, thereby bridging a critical gap in performance assessment methodologies [13].

Start with the basics: power transmission performance. Pay attention to how efficient the system runs at full load, its average efficiency across the whole offset range, how much power swings up and down, and the peak charging power it can reach. Now, anti-offset adaptation—what's that about? You're looking at the workable lateral offset, how much power drops when you hit segment gaps, and how well the chassis tolerates shifts in the air gap. Switching gears, think about engineering economic cost. This means tallying up construction costs for the track per kilometer, figuring out the material expenses for on-board equipment, and calculating annual operation and maintenance fees. The fourth piece is on-board lightweight adaptation. You need to look at the total coil weight, space taken up by the chassis, and any extra energy the vehicle burns because of it. Last up: electromagnetic safety compatibility. Basically, you're checking for magnetic field leakage strength, whether there's interference with weak current gear on board, and if everything meets the national electromagnetic safety rules.

This evaluation system transcends the conventional constraints of relying solely on a single efficiency metric by comprehensively considering both technical performance and commercialization factors. Consequently, it serves as a robust and objective foundation for guiding solution selection, facilitating simulation comparisons, and supporting informed decisions in engineering applications, as evidenced by reference [13].

6. DEVELOPMENT TRENDS AND FULL TEXT SUMMARY OF HOUSEHOLD PASSENGER CAR SCENE TECHNOLOGY

6.1 Core Technology Iteration Direction

Magnetic coupling coils are set to evolve, embracing thin, lightweight composite materials that boast high magnetic permeability, alongside the adoption of micro multi-coil arrays. As we strive to manage both weight and volume effectively, there's a concurrent focus on enhancing their two-way anti-offset capabilities. Furthermore, by optimizing the composite magnetic shielding structure, we aim to minimize magnetic field leakage and streamline the design process for vehicle electromagnetic compatibility.

For resonant topology, make the switch drive circuit in the reconfigurable topology simpler and reduce the computing power needed for the controller. Create a lightweight composite topology that works well with multiple pickup branches, balance how well it can stabilize voltage under different operating conditions with its hardware costs, and slowly replace the complicated double-sided LCC topology.

When considering the control algorithm, a notable shift is occurring where external position sensors placed on the road surface are being phased out. Instead, the system now relies solely on electrical data from the input side to calculate mutual inductance and accurately identify the vehicle's position. Furthermore, to cater to the needs of cost-effective, everyday household electric vehicles, a lightweight balancing and segmented switching algorithm

has been innovatively developed. This algorithm not only reduces the hardware demands on the vehicle controller but also ensures seamless adaptability to a wide range of affordable electric vehicles.

6.2 Phased Industrialization Implementation Path

Initially, in the short term, our focus will be directed towards low-speed commuter roads within enclosed environments such as parks, ports, and airports. This strategic move aims to gather valuable engineering test data while simultaneously driving down hardware production costs. Subsequently, as we progress into the medium term, our efforts will expand to encompass high-speed service areas and designated charging roads tailored specifically for urban buses, ensuring a more comprehensive and efficient transportation network. Looking ahead to the long term, our overarching goal is to achieve widespread coverage across the city's main thoroughfares, collaborating closely with smart grid time-sharing dispatch systems. This partnership will be instrumental in stabilizing the load pressure that arises during charging peaks, thereby alleviating the strain on the distribution network.

6.3 Industry Supporting Development Direction

It is imperative to expedite the establishment of national standards concerning dynamic wireless charging coils, communication protocols, as well as testing and evaluation procedures. Concurrently, constructing a vehicle-road-grid coordinated dispatching platform is crucial; this platform will effectively manage and stabilize grid load fluctuations by implementing time-sharing restrictions on charging power. Furthermore, to drive down the overall system costs and facilitate the widespread adoption of this technology for civilian applications, we should focus on developing low-cost soft magnetic materials and high-frequency power devices, thereby addressing cost reduction at the material level.

6.4 Full Text Summary

This article dives into a dynamic wireless charging system built around segmented guide rails and multi-pickup coils on vehicles. We get into the heart of the tech—magnetic coupling coils, resonance compensation topology, driving balance control—and show how each piece functions, how they've changed, and why they matter. On the practical side, we line up two major approaches: foreign long guide rails versus domestic park static arrays. It's a pretty stark contrast, showing just how differently researchers inside and outside the country approach the same problem. But there's more to this than just theory. We look straight at the real-world hurdles: technical roadblocks, engineering limits, gaps in industry standards. To cut through the noise, we set out five specific, quantitative evaluation metrics tailored for everyday electric vehicles. With those, we pin down where things stand now and where they're actually heading—especially in coil design, compensation topology, and control algorithms. In the end, we lay out an actionable roadmap for gradual commercialization. Here's what needs to happen next if this technology's ever going to go mainstream.

This article addresses current issues in vehicle dynamic wireless charging, like fragmented theories, no special study of composite designs, and no complete evaluation standards. It enhances the theory for segmented-multi-pickup composite systems. The findings offer theoretical guidance for coil modeling, improving topology, anti-interference control algorithms, and multi-objective optimization. They also provide an objective basis for road infrastructure and car companies when choosing solutions, helping to promote and implement dynamic wireless charging technology for household new energy vehicles.

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