iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** V **Month of publication:** May 2025

DOI: https://doi.org/10.22214/ijraset.2025.71270

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue V May 2025- Available at www.ijraset.com

Wireless Power Transfer Systems for Electric Vehicle Charging: Technologies, Challenges, and Future Prospects

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***Abstract:** The global shift toward electric vehicles (EVs) is vital for cutting emissions and fossil fuel reliance, but widespread adoption hinges on charging infrastructure. Conventional plug-in systems, though effective, face challenges like mechanical wear, safety risks, user inconvenience, and scalability limits. Wireless Power Transfer (WPT) offers a transformative alternative, enabling contactless, automated charging through electromagnetic fields. This paper examines the principles, technologies, challenges, and future of WPT for EVs.*

Inductive and magnetic resonance coupling are key WPT methods for EVs. Inductive charging uses coils and alternating magnetic fields for short-range power transfer, while resonant coupling enhances efficiency and range via synchronized transmitter-receiver frequencies. These systems support static charging (stationary vehicles) and dynamic charging (power transfer during motion on equipped roads). WPT eliminates physical connectors, improving safety and user experience while enabling operation in harsh environments. Integration with smart grids also allows optimized renewable energy use.

However, WPT faces hurdles. Efficiency depends on coil alignment, air gap distance, and electromagnetic interference (EMI), raising performance and safety concerns. High infrastructure costs, especially for dynamic systems, and a lack of standardization (varying coil sizes, frequencies) hinder scalability. Biological safety and EMI regulations must also be addressed. Future advancements may integrate WPT with AI and IoT for intelligent energy management, adapting to grid load, battery status, and user needs. Coupled with renewables, WPT could enable greener charging. Growing government and private sector investments in R&D and pilot projects signal strong potential for WPT to reshape sustainable transportation..

Keywords:** Electric Vehicles (EVs), Wireless Power Transfer (WPT), Electromagnetic Interference (EMI), Artificial Intelligence (AI), Internet of Things (IoT).

I. INTRODUCTION

The rapid global adoption of electric vehicles (EVs) is fueled by the urgent need to combat climate change[1], improve urban air quality, and transition to renewable energy. While EVs promise environmental and economic benefits, their widespread adoption hinges on overcoming limitations in charging infrastructure[2]. Conventional plug-in systems, though widely used, face challenges such as user inconvenience, safety risks from exposed connectors, cable degradation, and time-consuming manual processes.

Wireless Power Transfer (WPT) technology offers a transformative solution by enabling contactless energy transmission via electromagnetic fields[3]. By eliminating physical connectors, WPT enhances convenience through automated charging and reduces safety hazards like electric shocks[4]. Its potential extends to dynamic charging, where EVs recharge while moving on specially equipped roadways, minimizing downtime and extending driving range[5]. Key WPT methods include inductive coupling, magnetic resonance coupling, capacitive coupling, and microwave transmission. For EVs, inductive and resonant coupling dominate due to their efficiency over short-to-medium distances. These systems rely on aligned coils—a ground-embedded transmitter and a vehicle-mounted receiver—that transfer power via magnetic fields when tuned to resonant frequencies. Innovations in static (stationary) and dynamic (in-mtion) charging are reshaping EV infrastructure. However, WPT faces significant hurdles. Efficiency drops due to coil misalignment, air gaps, and electromagnetic interference (EMI) remain critical technical challenges. High infrastructure costs, particularly for dynamic systems requiring road modifications, and the lack of universal standards hinder scalability. Safety concerns, including biological effects of prolonged EMI exposure and regulatory compliance, also demand attention.

This paper provides a comprehensive analysis of WPT systems for EV charging, examining their principles, current technologies, and real-world applications.

It identifies key challenges, such as cost and standardization barriers, and evaluates advancements like AI-driven energy management and pilot projects for dynamic charging. The study also explores WPT's future potential, including integration with smart grids for load balancing, coupling with renewables like solar and wind, and synergy with autonomous vehicle networks. By addressing technical, economic, and regulatory gaps, WPT could revolutionize EV infrastructure, supporting a sustainable, efficient, and user-centric transportation ecosystem. This research underscores the role of collaborative innovation among governments, industries, and academia in accelerating WPT adoption and achieving global decarbonization goals.

II. PRINCIPLES OF WIRELESS POWER TRANSFER

Wireless Power Transfer (WPT) (Figure 1) is a method of transmitting electrical energy from a power source to a load without any physical connectors or wires. It operates on the fundamental principle of electromagnetic induction[3], where a time-varying magnetic field induces a voltage across a coil placed within the field. In the context of electric vehicle (EV) charging, WPT allows energy to be transferred from a stationary or embedded source (such as a charging pad on the ground) to a vehicle's onboard receiver coil, enabling efficient and convenient charging without the need for plugs or cables[6]**. Energy Storage:** Battery storage systems, pumped hydro storage, and other energy storage technologies. Several methods of WPT exist, but the two most widely adopted for EV applications are Inductive Coupling and Magnetic Resonant Coupling. Other methods like Capacitive Coupling and Microwave/RF Transmission are less common due to limitations in range, safety, or power-handling capabilities[7]**.**

A. Inductive Coupling

Inductive coupling, also known as magnetic induction, is the most mature and widely used form of WPT. It works by creating a magnetic field in a primary coil (transmitter) through the flow of alternating current (AC). When a secondary coil (receiver) is placed within the magnetic field, an electromotive force (EMF) is induced in the receiver coil due to Faraday's Law of Electromagnetic Induction, allowing power to be transferred wirelessly[3].

B. Magnetic Resonant Coupling

Magnetic resonant coupling builds upon the basic inductive method but enhances efficiency by operating both coils at a resonant frequency[6]. Resonance occurs when the natural frequency of the transmitter coil matches that of the receiver, significantly improving energy transfer even over greater distances or misaligned positions[7].

C. Capacitive Coupling (Electric Field Coupling)

In capacitive coupling, energy is transferred through an electric field created between two conductive plates. This method is not widely used for EVs due to its limited power capacity and higher sensitivity to environmental factors.

D. Microwave and RF Power Transfer

This technique involves converting electricity into microwaves or radio frequencies, transmitting it through the air, and converting it back to electricity at the receiver. While promising for long-distance applications like satellite power transfer, it is generally not viable for EVs due to concerns over efficiency, safety, and directional control.

E. Efficiency and Coupling Factor

The efficiency of a WPT system depends on:

The coupling coefficient between the coils (a function of distance and alignment) The operating frequency The quality factor (Q) of the resonant circuit Load impedance matching and converter efficiency.

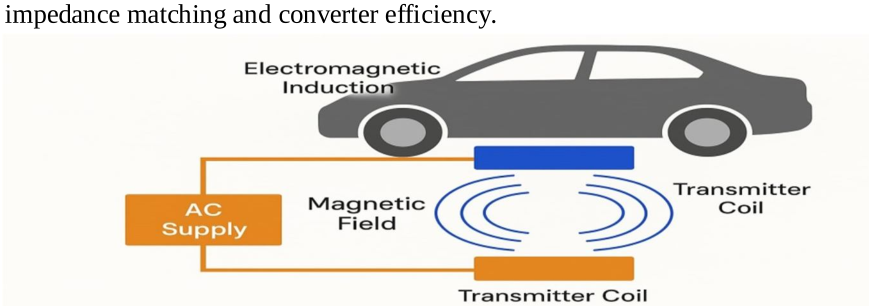

Figure 1. Principle of wireless transfer

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III. WPT TECHNOLOGIES FOR EV CHARGING

Wireless Power Transfer (WPT) technologies for Electric Vehicle (EV) charging have evolved rapidly over the past decade, offering efficient, safe, and user-friendly alternatives to traditional plug-in systems. These technologies are primarily based on inductive power transfer (IPT) and magnetic resonant coupling, with various configurations and implementations suited for both static and dynamic charging. This section discusses the key components, classifications, and real-world technologies used in WPT systems for EVs.

A. Static Wireless Charging

Static WPT refers to charging when the vehicle is stationary—typically parked in a garage, parking lot, or designated charging bay. This is currently the most mature form of wireless EV charging.

Example: WiTricity's DRIVE 11 system delivers up to 11 kW of power with over 90% efficiency[6]. Qualcomm Halo has demonstrated efficient static charging systems for cars and public transport.

B. Dynamic Wireless Charging

Dynamic WPT allows an EV to charge while in motion over a specially designed roadway embedded with transmitter coils.

Challenges: High infrastructure cost. Complex control systems to manage segment activation and billing. Road durability and maintenance issues.

Pilot Projects: Electreon (Israel) implemented a dynamic charging test track in Tel Aviv[8]. KAIST (Korea) developed the On-Line Electric Vehicle (OLEV) system for buses[9].

C. Bidirectional Charging (V2G Integration)

Modern WPT systems are evolving to support Vehicle-to-Grid (V2G) capabilities[10], where EVs can send electricity back to the grid during peak demand.

Key Technologies: Integration with smart grids. Power electronics capable of bidirectional flow. Real-time communication between the vehicle and grid operator. This transforms EVs into mobile energy storage units, contributing to grid stability and efficient energy use, especially when coupled with renewable energy sources[16].

D. Positioning and Alignment Systems

Efficient wireless charging relies on precise alignment between the transmitter and receiver coils. Misalignment can significantly reduce efficiency and cause energy losses.

Solutions: Electromagnetic field sensors. Automated parking systems with alignment guides. Wireless communication protocols (e.g., Bluetooth or ZigBee) to assist vehicle docking.

E. Safety and EMI Considerations

To ensure public safety and regulatory compliance, WPT systems incorporate: Shielding to limit electromagnetic field (EMF) exposure. Foreign object detection (FOD) to identify and shut down if a metal object interferes. Standards like SAE J2954 [4] and IEC 61980 to regulate design, safety, and interoperability[11]. In summary, WPT technologies for EV charging offer scalable, efficient, and futuristic alternatives to plug-in systems. While static charging is commercially viable today, dynamic charging represents the next frontier, promising continuous, on-the-go energy supply. The evolution of these technologies (Figure 2), along with smart grid integration and international standardization, will define the future of wireless EV infrastructure.

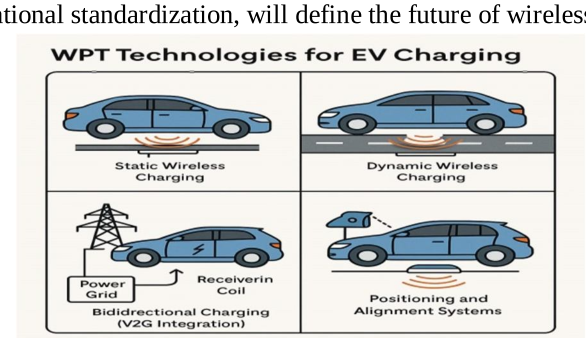

Figure 2. WPT Technologies for EV Charging

IV. ADVANTAGES OF WIRELESS POWER TRANSFER (WPT) FOR EV CHARGING

Wireless Power Transfer (WPT) offers several distinct advantages over conventional plug-in electric vehicle (EV) charging systems. These advantages span across convenience, safety, efficiency, and infrastructure optimization, making WPT an attractive technology for modern and future EV ecosystems.

A. Enhanced User Convenience

One of the most significant benefits of WPT is the elimination of cables and connectors:

- Charging is fully automated and hands-free, requiring no manual effort from the user.
- Especially beneficial for elderly or physically challenged users, and in environments like snow or rain where handling cables may be difficult.
- Seamless integration with automated parking systems supports a futuristic, user-friendly experience.

B. Improved Safety

WPT systems reduce the risk of electrical and mechanical hazards:

- No exposed conductors, reducing the risk of electric shock.
- Minimizes the chance of trip hazards or cable wear-and-tear.
- Integrated safety features like foreign object detection (FOD) and thermal management enhance operational safety.

C. Reduced Wear and Maintenance

Unlike plug-in systems that degrade over time due to repeated physical connection:

- WPT systems have fewer moving parts, resulting in less mechanical wear.
- Reduced maintenance costs over the long term.
- No connectors to replace, clean, or service.

D. Dynamic Charging Potential

Dynamic WPT enables charging on the move, which offers:

- Extended driving ranges without the need for frequent stops[9].
- Smaller battery packs (hence, lighter and cheaper vehicles).
- Possibility of endless range with continuous road-embedded charging systems.

E. Environmental and Urban Benefits

WPT can streamline infrastructure in cities and improve aesthetics:

- No clutter of charging poles or wires in public spaces.
- Facilitates cleaner urban designs and pedestrian-friendly environments.
- Potential integration with renewable energy sources and smart grid systems for sustainable energy management.

F. Support for Smart Grid and V2G Integration

WPT systems can be designed to support bidirectional power flow:

- Enables Vehicle-to-Grid (V2G) services where EVs act as mobile energy storage.
- Helps in grid load balancing during peak hours[16].
- Supports integration with IoT and cloud-based monitoring, enhancing energy efficiency and system intelligence.

In summary, Wireless Power Transfer offers transformative benefits for electric mobility. By enhancing convenience, safety, and scalability while paving the way for intelligent energy systems, WPT stands as a key enabler of the future of EV transportation.

V. CHALLENGES AND LIMITATIONS OF WIRELESS POWER TRANSFER (WPT) FOR EV CHARGING

While Wireless Power Transfer (WPT) presents a highly promising solution for EV charging, its widespread adoption is hindered by several technical, economic, infrastructural, and regulatory challenges. Addressing these issues is crucial for developing efficient, cost-effective, and safe WPT systems for electric vehicles.

A. Power Transfer Efficiency and Alignment Sensitivity

WPT systems are highly sensitive to coil alignment and distance:

- Misalignment between the transmitter and receiver coils reduces power transfer efficiency significantly.
- Air gaps or angular misalignment can lead to increased energy loss, making real-world performance inconsistent.
- Maintaining consistent alignment requires precision positioning systems or automated parking aids, adding to system complexity.

B. Electromagnetic Interference (EMI) and Safety Concerns

WPT systems operate at high frequencies, which can cause:

- EMI with nearby electronic devices, affecting their operation.
- Electromagnetic field (EMF) exposure to humans and animals, raising safety and health concerns.
- Strict compliance with safety standards (e.g., SAE J2954, ICNIRP guidelines)[11] is required to mitigate risks.

C. High Cost and Infrastructure Investment

Initial setup and development of WPT systems are expensive:

- Ground-side infrastructure (transmitters, inverters, control units) adds significant capital and installation costs.
- Dynamic charging roads require road modifications, which are expensive and disruptive[12].
- Onboard receiver systems also add to vehicle manufacturing costs.

D. Standardization and Interoperability

Lack of global standards creates issues such as:

- Compatibility between vehicles and chargers from different manufacturers is not guaranteed.
- Varying power ratings, coil sizes, and frequencies make universal adoption challenging.
- Incomplete standardization delays regulatory approval and large-scale implementation.

E. Limited Charging Power and Speed

Current WPT systems generally offer lower power levels than wired chargers:
Limited to 3.3 kW – 11 kW in most commercial applications (slower than DC fast charging).
Slower charging times may not be suitable for long-range or commercial EVs.
Higher power transfer is possible but leads to thermal issues and stricter safety demands.

F. Weather and Environmental Conditions

Although WPT systems are designed to be weather-resistant, challenges include:
Accumulation of dirt, snow, or water on coils may affect performance.
Outdoor installations may require additional protection or maintenance to sustain long-term efficiency.

G. Dynamic Charging Challenges

Dynamic WPT (charging while in motion) faces additional limitations:
Requires precise coordination between road transmitters and moving vehicles.
Involves complex control algorithms and billing mechanisms.

VI. RECENT DEVELOPMENTS AND CASE STUDIES IN WIRELESS POWER TRANSFER FOR EV CHARGING

The field of Wireless Power Transfer (WPT) for electric vehicles (EVs) has advanced significantly over the past few years, supported by collaborations between universities, technology companies, automakers, and government agencies. These efforts have led to successful pilot projects, commercial systems, and advancements in standards, paving the way for broader adoption. This section highlights some of the most notable recent developments and case studies.

A. WiTricity and the Global Standard (SAE J2954)[4]

WiTricity, a leading company in magnetic resonance WPT[6], has made key contributions to commercial EV wireless charging:

- Developed wireless systems capable of transferring up to 11 kW with over 90% efficiency.
- Their technology became the foundation for the SAE J2954 standard, published in 2020, which provides global guidelines for interoperability and safety[4].
- Collaborated with major automakers including BMW, Toyota, and Hyundai.

Impact: Standardization has enabled the development of compatible products across the EV ecosystem, ensuring safe, efficient, and widely usable wireless charging solutions.

B. Qualcomm Halo [7] and Dynamic Charging Tests

Qualcomm Halo, later acquired by WiTricity, developed WPT systems that were tested in both static and dynamic scenarios:

- Demonstrated dynamic wireless charging for EVs at speeds up to 100 km/h[13].
- Their technology was implemented in urban buses and test tracks in Europe and Asia.
- Notable Project: The FABRIC project in France (2014–2017) tested the feasibility of dynamic wireless charging over public roads, showing promising results for integrating this technology into future smart highways.

C. Electreon [8]- Dynamic Road Charging in Tel Aviv and Sweden

Electreon, an Israeli startup, has pioneered dynamic WPT[8]:

- Deployed inductive charging coils under roadways in Tel Aviv and Gotland, Sweden.
- Demonstrated successful wireless charging of public buses in motion over a 20-meter stretch.
- The system includes real-time energy management and vehicle-to-infrastructure communication.

Impact: Proved the feasibility of continuous, real-time charging of moving vehicles, reducing dependence on large batteries and charging stations.

D. KAIST – OLEV [9] Project in South Korea

The Korea Advanced Institute of Science and Technology (KAIST) developed the On-Line Electric Vehicle (OLEV) system:

- Buses powered by WPT while driving over roads embedded with resonant magnetic coils[9].
- Reduced battery size by up to 80% by enabling partial and continuous charging.
- Widely tested in public transport systems in South Korea.

Impact: OLEV demonstrated large-scale public transport viability, particularly for buses with fixed routes and schedules.

E. Academic Research and Prototypes

Numerous universities have contributed to WPT research[14]:

- Stanford University developed a highly efficient resonant WPT system capable of transmitting power over 90 cm with minimal loss.
- University of Auckland (New Zealand) has led projects on dynamic power transfer, control algorithms, and EMI mitigation techniques[15].

Impact: These academic efforts have improved the understanding of system design, power electronics, and optimization for real-world applications.

F. Conclusion of the Section

Recent advancements in WPT for EVs have transformed the concept from theory to reality. Whether through static or dynamic charging systems, public pilots or commercial products, the technology is steadily moving toward mainstream adoption. Ongoing investment in research, standardization, and infrastructure will be vital in overcoming remaining barriers and scaling WPT deployment across global transportation networks.

VII. FUTURE SCOPE OF WIRELESS POWER TRANSFER (WPT) FOR EV CHARGING

Wireless Power Transfer (WPT) holds vast potential to reshape the future of electric mobility. As global electric vehicle (EV) adoption accelerates, the demand for more convenient, efficient, and intelligent charging methods is rising. WPT, with its ability to deliver contactless energy, is at the forefront of this transformation. The future scope of WPT lies in technological innovations, mass adoption, integration with smart systems, and sustainable urban infrastructure.

A. Expansion of Dynamic Charging Infrastructure

Dynamic Wireless Power Transfer (DWPT) is expected to evolve significantly:

- Governments and private sectors may invest in electrified highways to enable real-time charging of EVs in motion.
- Future roads may include modular coil segments that activate only when needed, improving energy efficiency.
- Urban public transport (e.g., electric buses, trams) is likely to be early adopters of dynamic WPT, reducing downtime and battery size.

B. Integration with Smart Grids and V2G Systems

Future WPT systems will integrate seamlessly with smart grids, allowing:

- Vehicle-to-Grid (V2G) services[10], where EVs can return unused energy to the grid.
- Real-time energy management[16], dynamic pricing, and predictive analytics for load balancing.
- Decentralized energy ecosystems where EVs, renewables, and storage systems work in harmony.

C. Standardization and Mass Commercialization

With the success of standards like SAE J2954[4], the industry is moving toward:

- Global interoperability among EV manufacturers and charging equipment providers.
- Widespread inclusion of wireless charging receivers in future EV models as a standard feature.
- Lower costs due to economies of scale and simplified installation procedures.

D. Urban Planning and Smart City Integration

WPT will play a central role in smart city initiatives:

- Integration with autonomous parking systems, enabling automatic alignment and charging without human intervention.
- Use in multi-modal transit hubs, where cars, bikes, and buses can all charge wirelessly.
- Cleaner, safer public spaces due to the absence of cables and charging poles.

E. Technological Innovations and Research

Ongoing research will push the boundaries of WPT capabilities:

- Development of higher frequency resonant systems to enable faster, more efficient charging[18].
- AI and machine learning algorithms for adaptive power control and positioning.
- New materials (e.g., metamaterials, superconductors) to enhance magnetic coupling and reduce losses[16].

F. Environmental and Energy Benefits

As WPT becomes more efficient and widespread, it can:

- Reduce the reliance on large EV batteries, lowering vehicle weight and environmental impact[19].
- Enable better integration with renewable energy sources through intelligent grid connectivity.
- Promote sustainable energy use in the transportation sector.
- Conclusion of the Section

The future of Wireless Power Transfer in EV charging is not just promising—it is transformative. As technology matures and infrastructure expands, WPT could become the backbone of next-generation electric transportation, offering unprecedented convenience, scalability, and sustainability. Its integration with autonomous vehicles, smart grids, and green energy solutions will make it a cornerstone of the mobility revolution.

VIII. CONCLUSION

Wireless Power Transfer (WPT) technology represents a transformative innovation in the field of electric vehicle (EV) charging[16]. By enabling contactless energy transfer through inductive or resonant coupling, WPT addresses many of the limitations posed by conventional plug-in charging methods[20]. It offers significant benefits such as enhanced user convenience, improved safety, reduced maintenance, and the potential for dynamic, in-motion charging[17].

Over the past decade, notable advancements in WPT systems—from academic research to real-world pilot projects—have demonstrated the viability and effectiveness of both static and dynamic wireless charging[15].

Projects like Electron's dynamic roads in Israel, KAIST's OLEV buses in South Korea, and the adoption of global standards such as SAE J2954 underscore the growing momentum of this technology in mainstream EV infrastructure.

Despite its advantages, WPT still faces challenges including power efficiency, alignment sensitivity, high costs, and electromagnetic safety concerns[9]. Addressing these hurdles requires ongoing research, standardized protocols, and coordinated efforts between government, industry, and academia[15].

Looking forward, the integration of WPT with smart grids, renewable energy sources, and autonomous systems holds immense promise. As cities evolve into smarter, more sustainable environments[6], WPT is likely to become a key enabler of intelligent transportation networks, facilitating real-time, efficient, and user-friendly EV charging[21]. In conclusion, Wireless Power Transfer is not merely an alternative to wired charging—it is a critical pathway toward realizing the future of electric mobility, offering a seamless bridge between energy, technology, and transportation.

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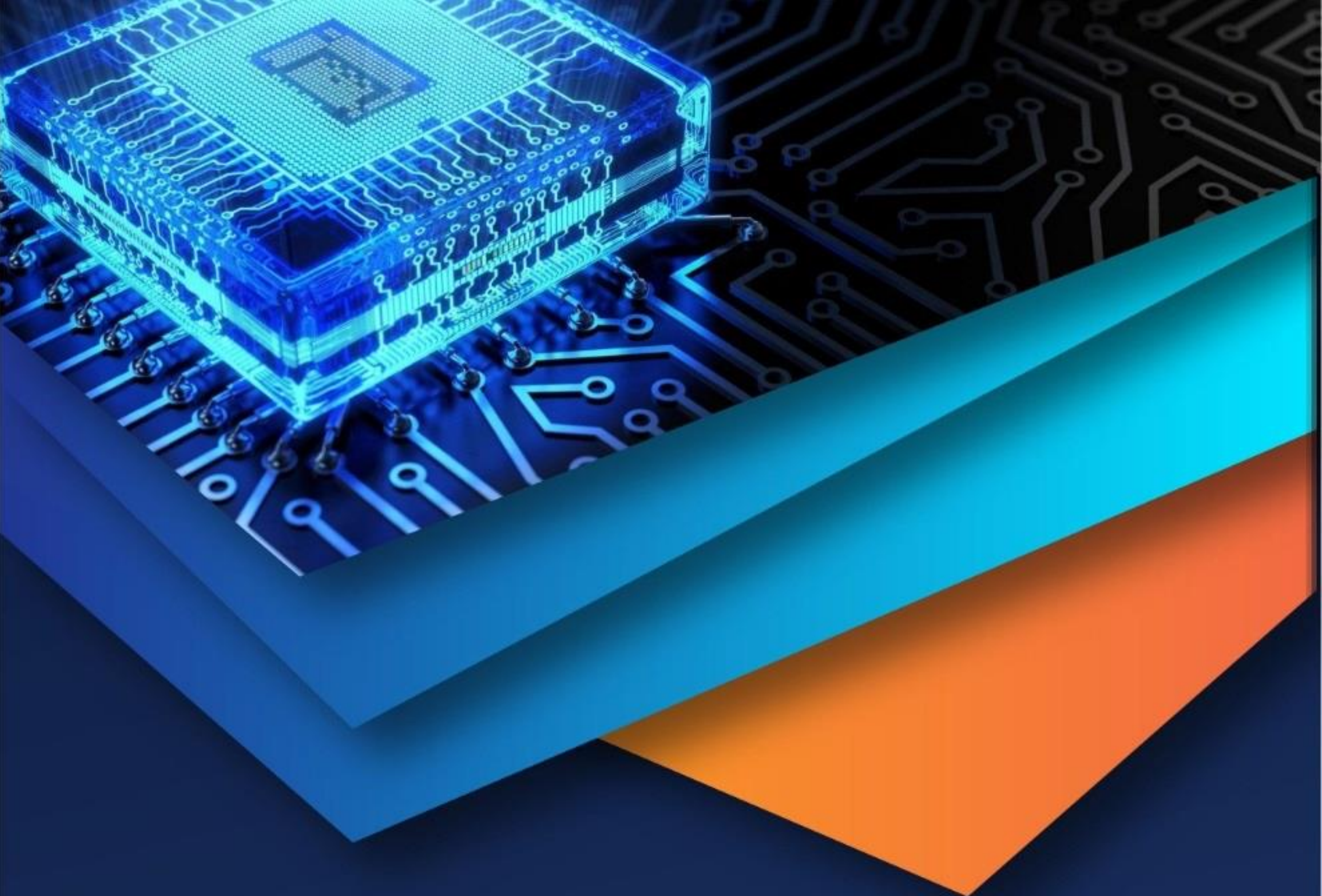

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