African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 2, Issue 4, October - December 2023, Page No: 187-197
Website: https://aaasjournals.com/index.php/ajapas/index
||Arab Impact factor 2022: 0.87|| SJIFactor 2023: 5.689|| ISI 2022-2023: 0.557

Emerging Trends in Wireless Electric Vehicle Charging Systems: Advancements and Challenges

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Received: September 09, 2023	Accepted: October 20, 2023	Published: October 25, 2023

Abstract:
Today, the adoption of electrified transportation presents a significant opportunity to mitigate greenhouse gas emissions and address the challenges posed by rising fuel costs. To facilitate the widespread adoption of electric vehicles (EVs), it is crucial to establish diverse and user-friendly charging networks that are environmentally sustainable. Wireless electric vehicle charging systems (WEVCS) have emerged as a promising alternative technology, offering the potential to address the limitations associated with plug-in charging methods. This paper provides an overview of the existing wireless power transfer technologies available for EVs, highlighting their potential to revolutionize the charging infrastructure and enhance the convenience and accessibility of EV charging. Moreover, the communication network within the IoE relies on an internet-like information flow, enabling bidirectional data exchange between devices. Reliability and connectivity enhancement are key considerations for the communication systems employed. Overall, the integration of EVs and the IoE framework holds immense potential for revolutionizing the power system, optimizing energy utilization, and promoting sustainable energy practices.

Keywords: Electric vehicles, Wireless charging system, Wireless power transfer, Internet of Energy (IoE), Charging Procedure, and Communication Protocols.

Cite this article as: A. Alkurbo, R. Elbasir, T. Eseholi, O. Abuzaid, Y. Abueejela, “Emerging Trends in Wireless Electric Vehicle Charging Systems: Advancements and Challenges,” *African Journal of Advanced Pure and Applied Sciences (AJAPAS)*, vol. 2, no. 4, pp. 187–197, October - December 2023.

الاتجاهات الناشئة في أنظمة شحن المركبات الكهربائية اللاسلكية: التطورات والتحديات

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الملخص
اليوم، يمثل اعتماد وسائل النقل المكهربة فرصة كبيرة للتخفيف من انبعاثات الغازات الدفيئة ومواجهة التحديات التي يفرضها ارتفاع تكاليف الوقود. لتسهيل اعتماد السيارات الكهربائية على نطاق واسع، من الضروري إنشاء شبكات شحن متنوعة وسهلة الاستخدام ومستدامة بيئيًا. ظهرت أنظمة شحن المركبات الكهربائية اللاسلكية **(WEVCS)** كتقنية بديلة واعدة، مما يوفر إمكانية معالجة القيود المرتبطة بطرق الشحن الإضافية. تقدم هذه الورقة نظرة عامة على تقنيات نقل الطاقة اللاسلكية الحالية المتاحة للمركبات الكهربائية، مع تسليط الضوء على قدرتها على إحداث ثورة في البنية التحتية للشحن وتعزيز راحة وإمكانية الوصول إلى شحن المركبات الكهربائية. علاوة على ذلك، تعتمد شبكة الاتصالات داخل إنترنت الأشياء **(IoE)** على تدفق معلومات يشبه الإنترنت، مما يتيح تبادل البيانات ثنائي الاتجاه بين الأجهزة. تعد الموثوقية وتعزيز الاتصال من الاعتبارات الرئيسية لأنظمة الاتصالات المستخدمة. بشكل عام، يحمل تكامل المركبات الكهربائية وإطار إنترنت الأشياء إمكانات هائلة لإحداث ثورة في نظام الطاقة، وتحسين استخدام الطاقة، وتعزيز ممارسات الطاقة المستدامة.

الكلمات المفتاحية: المركبات الكهربائية، ونظام الشحن اللاسلكي، ونقل الطاقة لاسلكيًا، وإنترنت الطاقة (IoE)، وإجراءات الشحن، وبروتوكولات الاتصال.

INTRODUCTION

Wireless Charging Systems (WCS) have garnered significant attention as a prospective solution for high-power implementations, notably in Electric Vehicles (EVs) and Plug-in Electric Vehicles (PEVs) deployed in static scenarios. When contrasted with plug-in charging systems, WCS offers many advantages in terms of its inherent simplicity, reliability, and user-friendliness. However, a fundamental constraint or drawback associated with WCS is their restricted utility exclusively when the vehicle is stationary or parked, such as in designated parking areas, garages, or at traffic intersections [1-3].

Furthermore, stationary Wireless Charging Systems (WCS) present various formidable challenges, including but not limited to concerns regarding electromagnetic compatibility (EMC), restricted power transfer capabilities, unwieldy physical structures, a limited operational range, and diminished efficiency. To address these limitations and enhance both the range capacity and volumetric adequacy of battery storage, extensive research has been conducted on the dynamic mode of operation for WCS in the context of EVs [4,5].

This approach facilitates the charging of battery storage devices during vehicular locomotion, thereby necessitating a reduced allocation of costly battery storage volume and augmenting the range capacity for transportation purposes [6-10]. Nevertheless, implementing a dynamic WCS encounters two primary obstacles, namely the substantial air gap and coil misalignment, which must be overcome before achieving widespread acceptance. The efficacy of power transfer is contingent upon the alignment of coils and the spatial separation between the transmitting source and the receiving apparatus.

The average magnitude of the air-gap distance typically ranges from 150 to 300 mm when considering small passenger vehicles, and it has the potential to increase further in the case of larger vehicles. In the dynamic mode of operation, the alignment of the optimal driving position concerning the transmitter coil can be effortlessly achieved, given that the vehicle is autonomously propelled [11-14]. Moreover, diverse compensation techniques, including series and parallel configurations, are employed on both the transmitting and receiving ends to mitigate parasitic losses and enhance overall system efficiency.

A significant contribution of wireless electric vehicle charging systems utilizing the Internet of Energy (IoE) framework, charging procedures, and communication protocols is the establishment of efficient and convenient charging infrastructure for electric vehicles (EVs). By integrating wireless charging technology with the IoE, EVs can be charged without needing physical plug-in connections, eliminating the inconvenience and potential hazards associated with traditional charging methods. This advancement enables seamless and automated charging procedures, enhancing the user experience and promoting the widespread adoption of EVs.

The IoE framework allows for intelligent management of the charging process, optimizing the utilization of available energy resources and ensuring efficient power flow. Charging procedures can be dynamically adjusted based on factors such as grid conditions, energy demand, and user preferences. This flexibility enables load balancing and peak shaving, reducing strain on the power grid and enhancing grid stability.

Communication protocols play a crucial role in facilitating effective data exchange and control between the charging infrastructure, EVs, and the grid. Standardized protocols such as ISO/IEC 15118 and Open Charge Point Protocol (OCPP) enable secure and reliable communication, allowing EVs to exchange essential information such as state of charge (SoC), charging power, and customer identification. These protocols enable interoperability among different charging stations, service providers, and EV models, ensuring compatibility and ease of use for EV owners.

The combination of wireless charging systems, the IoE framework, and robust communication protocols leads to a transformative charging infrastructure that enhances the convenience, efficiency, and scalability of EV charging. It enables seamless integration of EVs into the existing power grid, optimizing energy utilization and promoting sustainable transportation. This significant contribution accelerates the transition to a cleaner and more sustainable transportation ecosystem, reducing greenhouse gas emissions and dependency on fossil fuels.

WIRELESS CHARGING SYSTEM FOR EVS

The increasing demand for Electric Vehicles (EVs) has spurred significant interest in developing efficient and convenient charging solutions. One promising technology that addresses these concerns is the Wireless Charging System (WCS). This technology enables the transfer of power from a stationary charging infrastructure to the EV without physical connections, offering a seamless and user-friendly charging experience. The WCS operates based on the principles of electromagnetic induction and resonant coupling, allowing for efficient wireless power transfer [15-18].

The working principle of wireless power transfer (WPT) is rooted in the fundamental concept of magnetic resonance, which entails the oscillation of energy between two distinct modalities. Within a resonant system, the potential for substantial energy storage is realized through optimal excitation. When the oscillating energy surpasses the energy dissipation within the system, energy accumulation takes place. In the context of WPT, this oscillation manifests as an interplay between the electric field and magnetic field of a capacitor and an inductor, respectively [19-22].

To establish the transmission of power from the transmitting coil to the receiving coil, the alternating current (AC) mains sourced from the electrical grid undergoes conversion into high-frequency (HF) AC employing AC/DC and DC/AC converters [23-25]. The incorporation of compensation topologies based on series and parallel combinations is employed on both the transmitting and receiving ends to enhance the comprehensive efficiency of the system. The fundamental block diagram outlining the static WCS architecture designed for EVs is depicted in Figure 1.

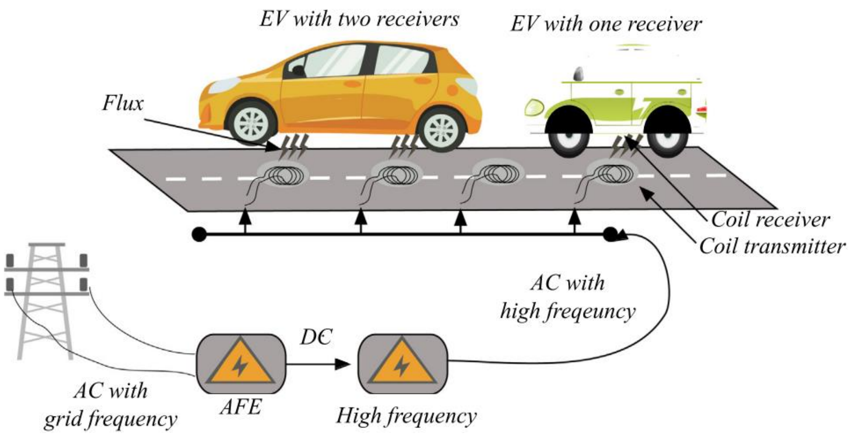

Figure 1. Block diagram outlining the static WCS architecture designed for EVs [26].

The receiving coil, conventionally positioned beneath the vehicle, facilitates the conversion of oscillating magnetic flux fields into high-frequency (HF) alternating current (AC). Subsequently, the HF AC is transformed into a steady direct current (DC) supply, which serves as the power source for the on-board batteries. To ensure stable operation and prevent any potential health and safety concerns, the system incorporates power control mechanisms, communication protocols, and a battery management system (BMS). Additionally, the utilization of magnetic planar ferrite plates at both the transmitter and receiver ends is implemented to mitigate the emission of deleterious leakage fluxes and optimize the distribution of magnetic flux.

Wireless power transfer methods

Since the advent of wireless charging systems for Electric Vehicles (EVs), the design of Wireless Electric Vehicle Charging Systems (WEVCS) has incorporated four prominent methods. These methods include traditional inductive power transfer (IPT), which relies on the mutual induction between the transmitting and receiving coils to transfer power wirelessly. Capacitive wireless power transfer (CWPT) utilizes electric fields to transfer power, employing capacitors to store and deliver electrical energy. Magnetic gear wireless power transfer (MGWPT) employs the concept of magnetic gears, where rotating magnetic fields are used to transmit power between the charging pad and the vehicle. Resonant inductive power transfer (RIPT) utilizes resonant circuits, enabling efficient power transfer through resonant coupling between the transmitting and receiving coils. These diverse approaches in WEVCS design showcase the continuous advancements in wireless charging technology for EVs [27,28]. Table 1 provides a comprehensive overview of the available wireless power transfer technologies specifically designed for battery-operated electric vehicles (BEVs).

TABLE 1, A BRIEF DESCRIPTION OF SEVERAL WIRELESS POWER TRANSFER (WPT) TECHNOLOGIES FOR EVs.

WPT methods	Power Level	Price	Feasibility to WEVCS	Efficiency
Resonant inductive	Low/Medium	Medium/High	High	High
Capacitive	Low	Low	Medium	Medium
Permanent magnet	Medium	High	Medium	Medium
Inductive	High	Medium	High	Medium

Capacitive wireless power transfer(CWPT)

The cost-effectiveness and inherent simplicity of capacitive wireless power transfer (CWPT) technology, facilitated by the implementation of advanced geometric and mechanical configurations in the coupling capacitors, render it highly advantageous for low-power applications. This includes the efficient charging of portable electronic devices, cellular phone chargers, and even rotating machines. Figure 2, depicts a representative schematic diagram illustrating the configuration of a series resonant circuit-based capacitive wireless power transfer (CWPT) system. Within the CWPT framework, the transfer of power from the source to the receiver is facilitated by the utilization of coupling capacitors rather than traditional coils or magnets [29-35]. The primary alternating current (AC) voltage is applied to an H-bridge converter utilizing power factor correction circuitry, thus enabling the efficient operation of the CWPT system.

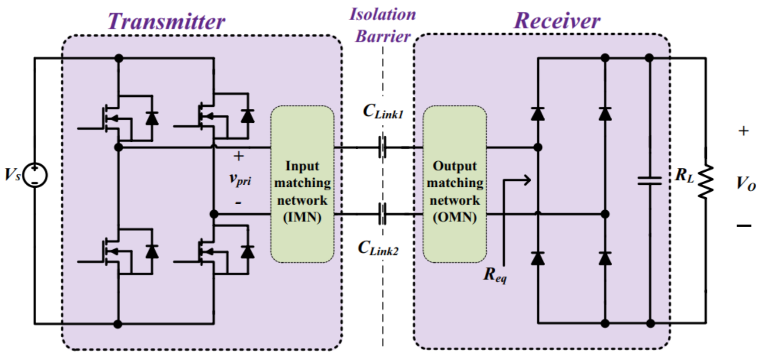

Figure 2. Circuit-based capacitive wireless power transfer (CWPT) system [36].

The high-frequency alternating current (AC) produced by the H-bridge configuration traverses through the coupling capacitors located at the receiver end. Unlike inductive power transfer (IPT), capacitive wireless power transfer (CWPT) operates effectively for both high voltage and low current scenarios. To minimize impedance between the transmitter and receiver sides within the resonant arrangement, additional inductors are introduced in series with the coupling capacitors. This configuration not only facilitates smoother switching within the circuitry but also helps maintain efficient power transfer. Similarly, the received AC voltage is converted into direct current (DC) for the battery bank or load through the utilization of a rectifier and filter circuitry. The power transfer capability is predominantly influenced by the size of the coupling capacitor and the distance between the two plates [37-44].

Magnetic gear wireless power transfer

The Magnetic Gear Wireless Power Transfer (MGWPT) method distinguishes itself from Capacitive Wireless Power Transfer (CWPT) and Inductive Power Transfer (IPT) techniques, as illustrated in Figure 3. Unlike conventional coaxial cable-based Wireless Electric Vehicle Charging Systems (WEVCS), MGWPT employs a configuration with two synchronized permanent magnets (PM) placed side by side. In this approach, the primary PM is subjected to the main power source, generating mechanical torque that results in its rotational motion [45,46].

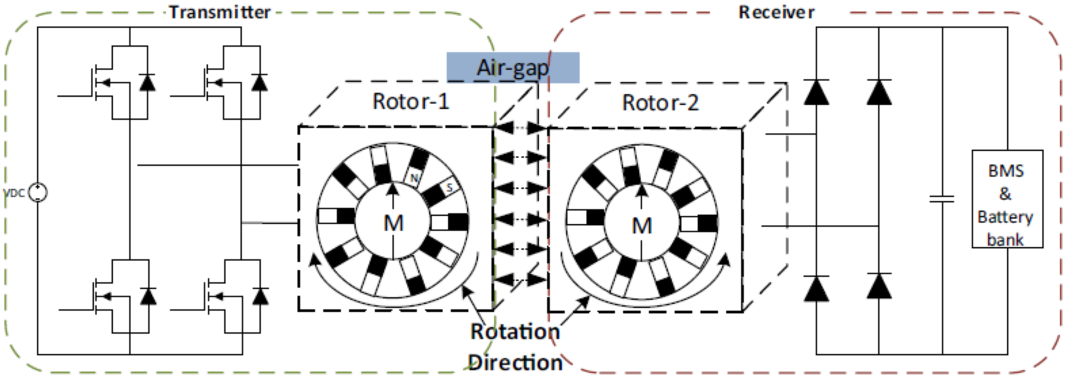

Figure 3. Schematic diagram of gear-based WPT

This mechanical torque is then transmitted to the secondary PM through mechanical interaction. Within the synchronized PM setup, the primary PM operates in generator mode, while the secondary PM receives the power and delivers it to the vehicle's battery through the power converter and Battery Management System (BMS). A laboratory prototype of MGWPT with a power capacity of 1.6 kW has been developed, demonstrating the ability to transfer power over an air gap distance of approximately 150 mm. However, the implementation of this technique in static and dynamic applications poses notable challenges that require further consideration and resolution.

Inductive power transfer (IPT)

Nikola Tesla introduced the concept of Traditional Inductive Power Transfer (IPT) in 1914 as a means to wirelessly transmit power. This technology has served as the basis for various Electric Vehicle (EV) charging structures. IPT has undergone extensive testing and has found widespread applications across a broad power range, from milliwatts to kilowatts, enabling the contactless transfer of power from a source to a receiver. Notably, in 1996, General Motors (GM) introduced the Chevrolet S10 EV, which utilized the Magne-charge IPT (J1773) system for Level 2 (6.6 kW) slow charging and Level 3 (50 kW) fast charging. The charging process involved inserting the primary coil, known as a charging paddle or inductive coupler, into the vehicle's charging port, thereby allowing the secondary coil to receive power and effectively charge the EV [48-52].

INTEGRATION OF EVS AND THE INTERNET OF ENERGY (IOE) FRAMEWORK

The integration of Electric Vehicles (EVs) with the Internet of Energy (IoE) framework represents a significant advancement in the realm of sustainable transportation and energy management. This convergence combines the capabilities of EVs as energy storage devices and the interconnectedness provided by the IoE, enabling intelligent and efficient energy utilization. By integrating EVs into the IoE framework, a dynamic and interactive ecosystem is created, where EVs can not only draw power from the grid but also contribute to grid stability and balance through vehicle-to-grid (V2G) technology. This integration opens up new possibilities for optimizing energy distribution, demand response management, and renewable energy utilization, ultimately leading to a more sustainable and resilient energy ecosystem. In this context, the integration of EVs and the IoE framework presents a transformative pathway toward the realization of smart and environmentally conscious transportation systems [53,54].

A. Charging Techniques

The charging process for Electric Vehicles (EVs) can be implemented in two distinct manners: controlled charging and uncontrolled charging. Uncontrolled charging entails the EV batteries initiating the charging process immediately upon connection to the charging station, or commencing after a user-defined delay, and continuing until the batteries reach full capacity or are disconnected. This charging method lacks integration strategies and does not consider grid conditions. While uncontrolled charging is a straightforward approach, it presents potential challenges for the utility grid. The uncontrolled charging method contributes to an increase in peak power demand, resulting in voltage fluctuations and overloads on distribution transformers and power lines. Consequently, as the penetration level of EVs in the grid rises, the reliability of the grid diminishes, necessitating mandatory grid reinforcement measures. Therefore, the uncontrolled charging approach, although simplistic, poses significant concerns for the stability and efficiency of the utility grid. To mitigate these challenges and enhance grid reliability, the implementation of controlled charging strategies and grid integration mechanisms becomes imperative [56,57].

In contrast, controlled charging encompasses the ability to schedule charging profiles for Electric Vehicles (EVs). The primary objective of this approach is to alleviate the adverse effects stemming from the integration of EVs into electrical grids. These effects encompass escalated load demand, the potential overload of system components, voltage and frequency imbalances, excessive harmonic distortion, and increased power losses. The ultimate aim is to maintain the stability of the distribution grid and defer the necessity for grid reinforcement. Undoubtedly, crucial considerations in implementing this charging method are the convenience of EV users and the economic incentives offered to foster their cooperation. Balancing the convenience of EV users with the overarching goals of grid stability and efficient energy management remains paramount. This entails developing charging strategies that prioritize user satisfaction while also incorporating mechanisms that deliver tangible economic benefits, thereby encouraging EV users' active participation and collaboration [58,59].

In contemporary times, the prevailing approach adopted by most utility providers is uncontrolled charging. As an alternative, a passive strategy known as the dual tariff strategy or "Time of Use" (TOU) pricing is commonly employed. Under this strategy, Electric Vehicle (EV) users are incentivized through financial rewards to shift their energy consumption to periods of low demand when electricity prices are lower, typically during off-peak hours such as nighttime. However, it is worth noting that dual tariff charging schemes may not necessarily yield the desired outcomes of demand profile smoothing, as the peak load is merely shifted to a different time within the day. Furthermore, as the widespread adoption of Vehicle-to-Grid (V2G), concepts is still limited, EVs primarily function as electrical loads for the distribution grid rather than active contributors. In the subsequent section, the present charging transaction processes and communication protocols employed in the context of EV charging will be elucidated.

B. Charging Procedure and Communication Protocols

The charging process of EVs involves a complex network of interconnected stakeholders, including charge point operators, e-mobility service providers, and roaming hubs. The charge point operator assumes responsibility for the operational and technical aspects of the charging infrastructure. This entails tasks such as access control, management, data collection, and maintenance. Additionally, the charge point operator may engage in commercial activities by procuring electricity from the supply market and offering charging services to EV users.

On the other hand, the e-mobility service provider plays a pivotal role in delivering e-mobility services to customers. Their primary responsibility lies in facilitating access to charging stations operated by various Charging Station Operators (CSOs). The e-mobility service provider serves as an intermediary, enabling EV users to utilize charging stations provided by different operators, thereby enhancing convenience and accessibility. The collaboration among these interrelated actors forms a comprehensive ecosystem that supports the charging process for EVs, ensuring operational efficiency, seamless access to charging infrastructure, and a smooth experience for e-mobility customers.

The communication between the EV and the charging station occurs via the pilot terminals, as discussed in earlier sections of this study, utilizing the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) 15118 standard. ISO/IEC 15118 is widely regarded as the preferred communication standard for this specific application. The exchanged data encompasses crucial information such as the state of charge (SoC) of the EV battery, permissible charging power levels, customer identification, and other pertinent details. By adhering to ISO/IEC 15118, the EV and charging station can establish a reliable and standardized communication interface, enabling seamless data exchange and efficient charging processes.

The Charging Station Management Software (CSMS), which serves as the backend system for charge station operators, frequently employs the Open Charge Point Protocol (OCPP) to facilitate remote control of the charging process via internet connectivity. OCPP is an open standard that leverages the WebSocket communication protocol and has emerged as the widely supported industry standard for communication between charging stations and CSMS. It provides compatibility for both AC and DC charging techniques.

By utilizing OCPP, charging stations establish communication channels with the CSMS, enabling effective management of charging points. Additionally, the CSMS interacts with the mobile application to facilitate operations such as reserving or canceling charging slots and providing real-time updates to EV users regarding the status of their vehicles throughout the charging process. The integration of OCPP with the CSMS and mobile application streamlines the management and coordination of charging operations, enhancing the user experience and optimizing the utilization of charging infrastructure.

The intelligent mobile applications deployed by e-mobility service providers serve as an intermediary platform connecting EV users with the Charging Station Management Software (CSMS). Through these applications, users receive comprehensive information regarding the charging process, including the injected charging power into their EV, the estimated completion time, and the associated costs for a full charge. These details are not only displayed on the charging station screen but are also accessible remotely via the user's mobile device.

Furthermore, these applications empower users with full control over the payment process, allowing them to conveniently manage the financial aspects of the charging transaction. Concurrently, the CSMS facilitates functionalities such as charge point reservation and cancellation by utilizing user identification tags and verifying the availability of charging slots. As a result, users can monitor the real-time availability of free charging slots within their vicinity and make reservations accordingly. Additionally, certain mobile applications incorporate navigation features to further enhance the user experience by guiding them to nearby charging stations.

C. IoE Framework

In the forthcoming era, the structural framework of the power system and its communication network will undergo a substantial transformation, deviating from its existing configuration. The traditional centralized model of power generation will be superseded by a decentralized arrangement referred to as a smart grid or Internet of Energy (IoE). This paradigm shift will engender significant alterations in the manner by which electric energy and information flow and disperse between the power system and end users. Moreover, the dominant source of energy supply will comprise an amalgamation of dispersed renewable energy installations, encompassing both small-scale and large-scale facilities [60,61].

Simultaneously, within the context of the IoE, both industrial and residential consumers will possess the capability not only to draw power from the grid but also to contribute surplus power as prosumers. In parallel, IoE aims to integrate diverse networks encompassing power, transportation, gas, and thermal systems into a unified entity. This integrated entity will facilitate energy exchange among a broad spectrum of sources and loads, including renewable energy sources, distributed energy storage, thermal systems, EVs, and prosumers. In essence, within the IoE framework, the reliance on large-scale power plants will be diminished, while the utilization of renewable energy sources will be substantially augmented. Each participant, such as energy devices and storage systems, will have the capacity to engage in energy trading by either selling or consuming energy. Furthermore, these participants will be seamlessly interconnected with the physical power system in a plug-and-play manner, akin to how a computer effortlessly detects and establishes communication with a USB device, thereby eliminating the necessity for extensive reengineering.

The communication fabric within IoT is predicated on an information dissemination framework akin to that of the Internet, commonly known as the IoT. This architecture facilitates bi-directional data interchange among devices, thereby fostering uninterrupted and fluid communication. The communication infrastructure that underpins the IoE can be established through wired connections, wireless technologies, or a hybrid amalgamation of both. As a result, every constituent within the IoE ecosystem possesses a discernible level of intelligence, which is complemented by a suite of essential apparatus such as sensors, smart meters, actuators, processing units, and communication modules. These components collectively enable the reception, processing, and transmission of information within the IoE network. The fundamental goal is to equip each IoE component with decision-making capabilities while establishing efficient channels of communication with other devices. It is crucial to underscore the necessity for the communication systems employed to exhibit robust reliability and enhance the connectivity between devices, thereby ensuring seamless and proficient transmission of data.

DISCUSSION AND FUTURE SCOPE OF EV

Static wireless charging systems involve stationary charging pads or plates embedded in the ground, typically installed in parking spots or garages. When an EV equipped with a compatible receiver park over the charging pad, power is wirelessly transferred from the pad to the vehicle, charging the battery. Static systems offer the advantage of easy and automated charging without the need for a manual connection. They are particularly suitable for overnight charging or long-duration parking scenarios, where the vehicle remains stationary for an extended period.

On the other hand, dynamic wireless charging systems enable charging while the EV is in motion. These systems typically utilize charging infrastructure embedded in roads or highways, and the EV is equipped with an onboard receiver that captures power as it drives over the charging tracks. Dynamic wireless charging allows for continuous charging, eliminating the need for frequent stops to recharge the battery. It holds the potential to significantly extend the range and utility of EVs, particularly for electric fleets and public transportation.

Furthermore, the initial endeavors towards the deployment of intelligent charging mechanisms, such as the adoption of the dual tariff strategy, have proven insufficient in effectively mitigating the challenges associated with integrating electric vehicles (EVs). The progression of EV commercialization will inevitably culminate in the establishment of an advanced grid infrastructure characterized by information dissemination capabilities and real-time regulation of power flow. This paradigm shift will facilitate the implementation of intelligent charging techniques and concepts, including Vehicle-to-Grid (V2G), Demand Response with Charging (DWC), and Quality of Service with Charging (QDWC). Moreover, as the imminent widespread integration of EVs ensues, accompanied by a concomitant surge in energy demand, there will be a pressing need to further harness Renewable Energy Sources (RESs). This imperative arises from the necessity to decarbonize the transportation sector, which inherently necessitates a substantial increase in the production of zero-carbon electricity.

CONCLUSION

the future scope of wireless EV charging systems is promising. Advancements in technology and standardization efforts are expected to improve the efficiency and reliability of wireless power transfer. Research and development initiatives are focusing on optimizing charging efficiency, increasing power transfer rates, and enhancing system interoperability.

In this direction, wireless EV charging systems offer unique advantages and present exciting possibilities for the future. The development and implementation of these technologies will play a crucial role in shaping the future of electric transportation, enhancing convenience, and addressing range anxiety concerns. Continued research, technological advancements, and collaborative efforts among stakeholders are vital to realize the full potential of wireless EV charging systems and drive the transition toward sustainable transportation.

In conclusion, the integration of wireless electric vehicle charging systems with the Internet of Energy (IoE) framework, along with advanced charging procedures and communication protocols, presents a significant advancement in the field of electric transportation. These technologies offer numerous benefits and pave the way for more convenient, efficient, and sustainable charging infrastructure for electric vehicles (EVs).

The combination of wireless charging systems, the IoE framework, and robust communication protocols represents a significant step towards a cleaner, more sustainable transportation ecosystem. It not only reduces greenhouse gas emissions and dependency on fossil fuels but also promotes the integration of renewable energy sources into the charging infrastructure. This convergence of technologies fosters the development of smart and interconnected energy networks, where EVs play an active role in grid management and energy optimization.

Overall, wireless electric vehicle charging systems utilizing the IoE framework, charging procedures, and communication protocols offer a transformative solution for the future of electric transportation. They enhance the convenience, efficiency, and scalability of EV charging, contributing to the widespread adoption of EVs and accelerating the transition towards a greener and more sustainable mobility landscape.

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