Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA29889

A Comparative Analysis of Wireless Power Transfer Technologies for Smart Grids

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Abstract. The smart grid is now an important direction for the development of the power system, which relies on wireless transmission technology to ensure that the grid runs fast and well. This article mainly examines the three wireless charging technologies used in the smart grid, namely inductive charging, harmonic charging and magnetic coupling charging, which are detailed to compare them. This paper focus on the basic principles of these technologies, their respective characteristics, where they can be used, and their benefits and disadvantages. The research found that each technology has its own advantages. This paper also discussed the future direction of development and felt that combining these technologies with intelligent control, while improving reliability, may be a good way to solve some of the problems facing us today, such as the issues of impermissibility and electromagnetic interference. This comprehensive development approach is very important for building smarter and more efficient power systems.

Keywords: Electromagnetic wireless transmission system, Coupled wireless charging transmission system, Resonant wireless transmission system, Smart grid

1. Introduction

Smart grids can be said to be the main trend in the future development of power systems, and what they want to do is to make the grid run more intelligently, efficiently, and reliably [1]. This grid uses many high-tech technologies, such as advanced sensors, communication equipment, computers, and control technologies, which can help the grid monitor and control the operation status in real time, so that power resources can be better distributed and used [2].

WPT technology has many advantages, such as being particularly easy to install and more flexible to use, as physical connectors are not required and security is improved [3]. These features make it suitable for use in complex systems such as smart grids to meet the changing needs of the grid in terms of energy transmission. However, WPT still encounters some difficulties when using smart grids on a large scale [4].

This paper mainly studies the principle, main features, application scenarios, and the comparison and analysis of the three mainstream wireless transmission systems, aiming to provide a reference for the application of wireless transmission technology in the future.

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DOI: 10.54254/2755-2721/2026.KA29889

2. Electromagnetic wireless transmission system

2.1. Basic principles and structure

In terms of basic principles and structure, electromagnetic wireless transmission systems are based on Faraday's law of electromagnetic induction, where the induced electromotive force

$$\epsilon = -N\frac{d\Phi}{dt} \tag{1}$$

where capital N is the number of coil turns and $\frac{d\Phi}{dt}$ is the rate of change of magnetic flux.

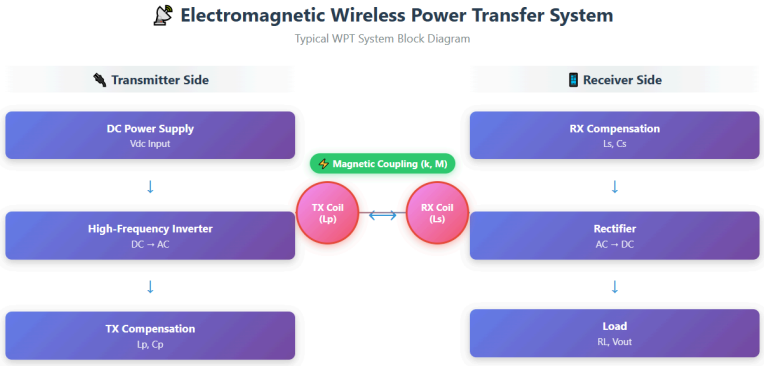

Figure 1. Typical WPT system block diagram

Figure 1 shows how an electromagnetic wireless power transfer system operates. The key parameters in Fig. 1 are defined as follows: V_dc is the DC input voltage; L_p and C_p are the primary inductance and compensation capacitance; L_s and C_s are the secondary inductance and compensation capacitance; k is the coupling coefficient; M is the mutual inductance; R_L is the load resistance; f is the operating frequency; and η is the transmission efficiency. The transmitted power P can be expressed in terms of the transmitter current I_1, the receiver current I_2, and the mutual inductance M:

$$P = \omega MI1I2 \tag{2}$$

Where ω is the angular frequency of the alternating current. The mutual inductance coefficient, capital M, depends on factors such as the number of turns, size, relative position, and core material of the transmitting and receiving coils [5].

In practice, compensation circuits are also added at the transmitter and receiver ends to improve transmission efficiency and stability. Compensation circuits can improve the power factor of the system, reducing the loss of reactive power and thereby maintaining better system performance under various loads and transmission distances.

2.2. Technical advantages and limitations

The electromagnetic wireless transmission system offers several advantages, including structural simplicity, low cost, and high efficiency over short ranges. It is well-suited for stable power supply scenarios and generally exhibits good electromagnetic compatibility and safety. The system also possesses a degree of extensibility.

DOI: 10.54254/2755-2721/2026.KA29889

However, its distance is limited, the efficiency decreases with the increase of distance, and the flexibility is insufficient.

2.3. Typical applications in smart grids

Electromagnetic wireless transmission systems find several promising applications within the smart grid architecture. In household energy management, it enables bidirectional communication between smart meters and the grid, facilitating the transmission of consumption data and tariff signals. This supports accurate billing and enables dynamic load regulation. In distributed power generation, it can efficiently complete power transmission and data interaction, and provide real-time feedback of power generation data from solar panels and wind turbines to the grid scheduling center. In electric vehicle charging, wireless charging during parking or driving can be achieved by laying transmitting devices, and optimizing charging time and power by combining grid load and tariff information [6].

2.4. Status of development and trends

The electromagnetic wireless transmission system in the smart grid has advanced quickly in recent years. At the technical level, with the progress of materials science, high-performance magnetic core materials have been steadily developed and implemented, effectively enhancing the transmission efficiency and power density of the electromagnetic wireless transmission system. For example, the use of certain new soft magnetic materials reduces core loss, significantly improving the system's short- and medium-distance transmission efficiency. On the application front, pilot projects and commercial deployments are expanding, particularly in distributed power generation and electric vehicle charging. In distributed power generation scenarios, they enable efficient wireless connections between power generation equipment and energy storage devices, lowering maintenance costs and safety risks associated with traditional cable connections. In electric vehicle charging, electromagnetic wireless charging pilot projects have been launched in some cities, offering a more convenient charging option for electric vehicles.

In the future, the electromagnetic wireless transmission system will become more and more powerful; not only will the power be greater, but the transmission distance will be farther. We can improve the electromagnetic design and control methods, so that the transmission efficiency is higher, the power density is also greater, and so that more distributed energy access and large-capacity energy storage needs can be supported. As the technology slowly matures, the cost of the system will slowly come down, and then it can be used in more places [7].

3. Coupled wireless charging transmission system

3.1. Electromagnetic coupling mechanism

This part of the system is what people usually call " coupled wireless charging"; in fact, it is the use of the electromagnetic induction principle mentioned in the previous Section 2 in real life. It is mainly based on the old method of electromagnetic induction. According to Faraday's discovery of the electromagnetic induction law, the energy is transferred from the transmitter to the receiving end. Because the basic principle of energy transmission is Faraday's law, this section of 2.1 has been very clear, so now this part is mainly to say that distinguish "coupled wireless charging" as a specific application domain.

The coupling efficiency is quantified by the coupling coefficient (k), a dimensionless parameter ranging from 0 (no coupling) to 1 (perfect coupling). The relationship between the coupling

DOI: 10.54254/2755-2721/2026.KA29889

coefficient k and the mutual inductance of the two coils, M, as well as their respective self-inductances, $L1$ and $L2$, is as follows:

$$k = \frac{M}{\sqrt{L1L2}} \tag{3}$$

Mutual inductance M denotes the ability of a current change in one coil to generate an induced electromotive force in another coil, which is related to factors such as the number of turns of the coil, its geometry, its relative position, and the magnetic medium, etc. The power transfer capability of the system is fundamentally dependent on ω, M, I_1, and I_2. In well-tuned systems operating at resonance, high power levels can be achieved, making this technology suitable for short-to-medium distance, high-power applications like electric vehicle charging.

In addition, there are energy losses in the electromagnetic coupling process, mainly including the resistance loss of the coil and the core loss of the magnetic core. These losses will reduce the transmission efficiency of the system, so when designing the electromagnetic coupling system, the design of the coil and the selection of the core material need to be optimized in order to improve the coupling efficiency and reduce the energy loss, so as to realize efficient wireless energy transmission.

3.2. System topology and key components

The topology and key components of a coupled wireless charging transmission system are critical to its performance and application. Common topologies include series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP). The SS topology is suitable for high stability scenarios, while the SP topology improves transmission efficiency and load adaptation. Key components include coupling coils, compensation capacitors, and power converters. The coupling coil is the core of energy transmission, and the design needs to consider factors such as the number of turns and wire diameter; the compensation capacitor is used for resonance to improve efficiency; and the power converter is responsible for the conversion of electrical energy, and the most common types are DC-DC and DC-AC. These components work in tandem to determine the system's performance and range of applications [8].

3.3. Technical advantages and limitations

Inductance power transmission technology, also known as IPT technology in practical applications, coupled wireless charging systems are now becoming more and more important, especially in the field of smart grid and electric vehicles. Many researchers are concerned about this technology. The main feature of this technology is that it can transmit energy without direct contact; the power is particularly large, the security is better, and the benefits of wireless charging are actually quite numerous. It can transmit hundreds of watts or even thousands of watts of power, which can fully meet the power requirements of electric vehicles, which is a good basis for the application of high-power wireless charging. The system is also highly automated, as long as the car is parked on the charging board, and the charging can be automatically started without a human touch. Due to the use of a closed magnetic coupling structure, long-term use is also reliable. The most powerful thing is that this technology can also achieve dynamic wireless charging, that is, the car is charging while driving, so that it does not have to install a large capacity battery, which is both power-saving and flexible.

DOI: 10.54254/2755-2721/2026.KA29889

Although there are many benefits to the coupled wireless charging system, there are still many problems to be solved in practical applications. The biggest problem with this system is that its charging efficiency is particularly dependent on the position relationship between the transmitting coil and the receiving coil; even if it is only slightly biased or the distance is not right, the charging effect will become very poor. In order to ensure that the system can work properly, it must have a very precise positioning and adjustment device. Precision positioning devices, plus inverters, rectifiers, and power electronics for compensation networks. These things add up to make production and maintenance very expensive, which will be a big problem at the beginning of the promotion. Another worrying thing is that the system will produce a strong magnetic field when working, which may affect human health, and will interfere with the surrounding electronic equipment, so protective measures must be taken [9].

3.4. Application cases and prospects in smart grid

The coupled wireless charging system demonstrates its advantages in the electric vehicle, smart home, and industrial sectors. Its unplugging and automation features enhance convenience and safety, and it is suitable for car parks, bus stops and home microgrids to optimize energy use. In the future, it is expected to support dynamic charging of electric vehicles and promote the integration of the smart grid and transport. It can also provide safe and reliable energy supply in special environments such as mines and underwater. With the improvement of efficiency and cost reduction, its application in the smart grid has great potential, which will help the efficient use of energy and sustainable development.

4. Resonant wireless transmission system

4.1. Harmonic coupling mechanism

The resonant wireless transmission system is based on the electromagnetic resonance principle and achieves efficient energy transmission through resonant coupling. When the resonant circuits at the transmitting and receiving ends are at the same frequency, an efficient energy transmission channel can be established. The power supply at the transmitting end excites the resonant loop to generate an alternating electromagnetic field, and the resonant loop at the receiving end captures energy at the same frequency. Resonant coupling has the advantages of high efficiency, low distance and angle sensitivity, and selective reception, which makes it suitable for smart grid and other scenarios.

4.2. System structure and tuning methods

A typical RWPT system comprises a transmitter and a receiver. The transmitter includes a DC power supply, a high-frequency inverter, a transmitting coil, and a resonant compensation network... Conversely, the receiver is composed of a pick-up coil, a resonant compensation network, a rectifier, and the load.

Precise tuning is critical for optimizing RWPT performance. Frequency tuning involves adjusting the excitation frequency to match the natural resonant frequencies of the transmitter and receiver circuits, thereby maximizing energy transfer efficiency. The resonant frequencies of the transmitter and receiver can be calculated by the following equation: for a series resonant circuit, the resonant frequency f_0

DOI: 10.54254/2755-2721/2026.KA29889

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

Where L is the coil inductance and C is the compensation capacitance.

Impedance matching tuning works by adjusting the impedance of the transmitter and receiver to conjugate and match for maximum power transmission. Common matching networks are L-type, T-type, and π-type networks for optimizing the impedance matching effect.

4.3. Technical advantages and limitations

Resonant wireless transmission system has unique technical advantages. Using the resonant coupling mechanism, it can achieve efficient energy transmission within a certain distance, with relatively high transmission efficiency and less influence by distance. The continuous improvement of the system structure and tuning method makes it possible to maintain better performance in different environments. The transmission direction of the resonant wireless transmission system has a certain degree of flexibility, which can be adapted to different positions and angles of the receiving equipment, and improves the convenience of use.

However, resonant wireless transmission systems also have limitations. The design and debugging of the system is more complicated, requiring precise parameter matching and tuning, which is technically demanding. The stability of the resonant frequency is easily affected by external environmental factors, such as temperature and humidity, which may lead to a decrease in transmission efficiency. In addition, the cost of the system is relatively high, especially when realizing long-distance and high-efficiency transmission, which requires the use of high-performance components and complex control algorithms, increasing the cost and complexity of the system.

4.4. Application cases and prospects in smart grids

Resonant wireless transmission system has been successfully applied in many aspects of the power grid. Distributed energy access, flexible and efficient transmission of electricity, such as wind farms in remote mountainous areas to transmit electricity to the substation, reducing costs and losses; wireless charging of electric vehicles, part of the city car parks installed this device to achieve automatic charging to enhance convenience; smart home interaction, can help home appliances optimize the use of electricity, reduce costs and ease the pressure on the grid. The future application of its broad prospects, transmission efficiency and distance will be improved, or build the city wireless power supply network; new energy vehicles is expected to become the mainstream charging mode, highway or paved facilities to achieve the charging of vehicles; smart microgrids, can promote the integration of distributed energy, optimize the distribution of energy, and help to build a smart energy Internet.

5. Comparison and analysis of three wireless transmission systems

5.1. Comparison of technologies (efficiency, distance, stability, cost)

In smart grids, there are significant differences in efficiency, distance, stability and cost among the three types of wireless transmission systems: electromagnetic, coupled, and resonant. Table 1 provides a detailed comparison of the characteristics of the three wireless transmission systems.

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In terms of transmission efficiency, resonant wireless transmission systems have significant advantages. When the resonant frequencies of the transmitter and receiver are matched, efficient energy transmission can be achieved with low energy loss. Under ideal conditions, its transmission efficiency can be as high as 90% or more. An electromagnetic wireless transmission system transmits energy through the principle of electromagnetic induction, and the efficiency is relatively low, generally around 70% - 80%

Table 1. The comparison and analysis of the main characteristics of three wireless transmission systems

specificities	Inductive (Electromagnetic)	Resonant	coupled
transmission efficiency	70%-80%	Over 90%	80%-90%
transmission distance	A few centimeters to tens of centimeters	several meters	Suitable for different application scenarios
System stability	susceptible to interference	Less affected by frequency	Component-dependent performance
cost analysis	lowest cost	relatively high	conveniently situated

Because a certain amount of heat loss occurs during the energy conversion and transmission process. Coupled wireless charging transmission system efficiency is between the two, usually can reach 80% - 90%, but the specific efficiency will be affected by the coupling coefficient and other factors.

In terms of transmission distance, resonant wireless transmission systems excel. Due to the resonance characteristics, it can achieve energy transmission at a relatively long distance, and the transmission distance can reach several meters or even more. Electromagnetic wireless transmission system transmission distance is generally shorter, generally between a few centimeters to tens of centimeters, which is determined by its electromagnetic induction principle. the distance is too far will lead to rapid attenuation of the magnetic field strength, and the energy transmission efficiency is greatly reduced. The transmission distance of the coupled wireless charging transmission system is also limited, usually between a few centimeters and about one meter, and its transmission distance is limited by the size and performance of the coupling element.

Stability, resonant wireless transmission system is relatively stable. As long as the resonant frequency is kept stable, the external environment has less influence on its transmission performance. An electromagnetic wireless transmission system is less stable, easily affected by external magnetic field interference and changes in the relative position of the device. When the relative position of the transmitting and receiving ends changes slightly, the transmission efficiency may drop significantly. The stability of the coupled wireless charging transmission system is general, and its stability depends on the performance of the coupling components and the anti-interference capability of the system.

In terms of cost, the electromagnetic wireless transmission system is less expensive. Its structure is relatively simple, mainly composed of coils and other basic components, and the manufacturing process is mature, so the cost is more affordable. The cost of a coupled wireless charging transmission system is moderate, due to the need for specific coupling components and control circuits; the cost will be higher than the electromagnetic wireless transmission system. Resonant wireless transmission systems are more costly, requiring precise resonant circuits and frequency control equipment, with relatively high R&D and manufacturing costs.

DOI: 10.54254/2755-2721/2026.KA29889

5.2. Application suitability analysis

Different wireless transmission systems have different applicability in the smart grid. The electromagnetic wireless transmission system has the characteristics of simple structure and mature technology, which is suitable for scenarios that do not require a high transmission distance but have certain requirements on transmission efficiency and stability. For example, in the wireless metering and information collection in the near distance, the electromagnetic wireless transmission system can stably transmit the metering data to the concentrator, and its relatively high transmission efficiency can ensure that the data are transmitted timely and accurately. Moreover, in the energy transmission between some small distributed power generation equipment and energy storage devices, an electromagnetic wireless transmission system can also play a good role due to the close distance [10].

The coupled wireless charging transmission system has certain advantages in transmission power and distance, and is suitable for wireless energy transmission and energy storage management, as well as electric vehicle charging scenarios. In wireless energy transmission and energy storage management, it can realize efficient energy transmission over medium distances and fast charging for energy storage devices. For electric vehicle charging, the coupled wireless charging transmission system can wirelessly charge a vehicle while it is in motion or while it is parked, improving the convenience and flexibility of charging. However, its system topology is relatively complex and costly, and the cost factor needs to be considered comprehensively in large-scale applications.

A resonant wireless transmission system has high transmission efficiency and long transmission distance, which is suitable for distributed power generation and electric vehicle charging scenarios. In distributed power generation, when the distance between the power generation equipment and the power-using equipment or the energy storage device is long, the resonant wireless transmission system can efficiently transmit the power. In electric vehicle charging, it enables wireless charging over longer distances, reduces the alignment requirements between the charging facility and the vehicle, and improves the convenience of charging. However, the tuning method of this system is more complicated, and its adaptability to the environment needs to be improved; and these technical difficulties need to be solved to better exploit its advantages in practical applications.

5.3. Summary of advantages and disadvantages

The advantage of electromagnetic wireless transmission system is that the principle and structure is relatively simple, easy to implement and maintain, and can ensure a certain transmission efficiency in the near distance transmission. Its limitation is that the transmission distance is relatively short, and the transmission efficiency will be significantly reduced with the increase of distance; at the same time, there is a certain electromagnetic radiation problem.

The advantages of the coupled wireless charging transmission system are that it is capable of achieving energy transmission over medium distances, the electromagnetic coupling mechanism makes it possible to reduce energy loss to a certain extent, and the system topology is relatively flexible. However, the system requires high-performance of key components, has a relatively high cost, and its stability in complex environments needs to be improved.

The outstanding advantages of the resonant wireless transmission system are that it can achieve a relatively long transmission distance while maintaining a high transmission efficiency and low sensitivity to position within a certain range. However, the tuning process of this system is more complicated, the matching requirements of the system parameters are strict, and the design and realization of the system are difficult.

DOI: 10.54254/2755-2721/2026.KA29889

Overall, the three types of wireless transmission systems each have their own advantages and disadvantages in terms of transmission efficiency, range, stability, and cost. In terms of application suitability, the electromagnetic type is appropriate for short-distance scenarios where cost and implementation complexity are of primary concern; the coupling type is suitable for medium-distance applications that require a certain balance between transmission efficiency and flexibility; and the resonant type is more suitable for long-distance situations where high transmission efficiency is required.

5.4. Comprehensive development trends and adaptation scenarios

The comprehensive development trend of wireless transmission in smart grids is characterized by multi-technology integration, intelligence and automation, as well as enhanced reliability and security.

Multi-technology integration is actually the combination of electromagnetic wireless transmission, coupled and harmonious wave wireless transmission technology, so as to play their respective strengths. For example, in long-distance transmission, the electromagnetic wireless transmission effect will be better, and coupling technology or harmonic technology is more suitable for short-distance transmission, so that the efficiency is higher. Now the wireless transmission technology is developing rapidly, it is slowly integrated with the Internet of Things, big data and cloud computing information technology, so that it can be used to collect the power grid operation data in real time, and can also be analyzed and processed.

Now, intelligence and automation have become a particularly important development trend. If wireless transmission systems can use new technologies such as artificial intelligence (AI) and machine learning (ML) algorithms, they can find problems, adjust settings, and continuously improve. When the grid load or the surrounding environment changes, the system can automatically change the transmission parameters, which can make the transmission more efficient and the system run more stably.

Because the smart grid is increasingly using wireless transmission technology, it puts forward higher standards for the stability and security of data transmission. In order to meet these challenges, future wireless transmission systems will adopt new methods, such as adding backup lines, setting up fault auto-processing functions, and using more advanced encryption technology.

This paper mainly discusses the application of radio force transmission technology in different scenarios. The harmonic radio power transmission system has a great advantage that it can achieve long-distance transmission, so it is particularly suitable for power transmission between distributed power generation equipment and the power grid. In addition, in terms of electric vehicle charging, this technology can also be used to enable the dynamic charging of vehicles during driving. For example, wind power plants can use this technology to send the electricity generated by wind turbines to the substation through electromagnetic wireless transmission, so that there is no need to lay so many transmission lines.

This paper mainly studies the wireless charging transmission system, which can improve the transmission efficiency well through the coupling technology, and the electromagnetic radiation is relatively low, so it is very suitable for wireless measurement and information collection, and can also play a good role in wireless energy transmission and storage management. For example, many smart meters are now using this coupled wireless charging technology, which can make the meter power supply without wiring, and realize wireless data transmission.

Harmonic radio transmission system in the middle distance and medium power transmission performance is very good. This system is particularly suitable for use in smart homes and smart

DOI: 10.54254/2755-2721/2026.KA29889

buildings, both for power supply and data transmission. Take the smart home, harmonic wireless transmission technology can provide wireless charging function for a variety of smart devices, so that it is more convenient to install, and more flexible to use.

6. Conclusion

This paper mainly examines the three wireless power transfer (WPT) technologies used in smart grids, namely electromagnetic induction, coupled resonant and harmonic systems. We have made detailed comparisons of these technologies together and found that they can make power transmission more flexible and convenient, and can supply power without a plug-in. Together, these technologies are helping our power systems become more intelligent and more environmentally friendly, and more efficient. The safety also needs to be improved, and the compatibility between different devices is not good enough; these problems make wireless charging technology temporarily unable to be promoted and used on a large scale.

One way to look at a more playful approach is to mix different wireless charging technologies, such as electromagnetism and coupling harmony, to create hybrid wireless charging systems. The advantage of this is that it can cope with a variety of charging environments, and the charging efficiency will not be too low. In addition, everyone is now studying how to make wireless charging smarter, such as using artificial intelligence and machine learning, so that the wireless charging system can adjust its working status and even automatically repair some minor problems.

Now there is a very interesting practice, which is to combine the electromagnetic induction and magnetic resonance of these different wireless charging technologies to create a hybrid wireless charging system. The biggest advantage of this hybrid system is that it can be used in a variety of different charging environments, and the charging effect is not too bad. Now many researchers are trying to make wireless charging smarter, such as adding artificial intelligence and machine learning technology, so that the wireless charging system can adjust its own working mode, and sometimes automatically solve some common problems.

In general, radio transmission technology is likely to revolutionize the future of smart grids. With the resolution of current technical challenges and the improved integration of interdisciplinary knowledge, WPT technology can drive the evolution of power systems toward higher intelligence, resilience, and sustainability.

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