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Review on wireless EV charging systems

A.Sh. Safonov[1], *T.A.* Khasanov[1], *Z.M.* Shakurova[1*], *A.R.* Safin[1], *L.V.* Dolomanyuk[1], and *V.A.* Gavrilov[1]

[1]Kazan State Power Engineering University", 51 Krasnoselskaya St., 420066 Kazan, Republic of Tatarstan

Abstract. The advent of electric vehicles in our daily lives has led to a growing need for charging infrastructure. In contrast to internal combustion engine (ICE) vehicles, electric vehicle charging takes a considerable amount of time. Several wireless charging systems for moving electric transport have been developed to address this issue, but each comes with its own set of usage limitations. By using inductive wireless charging systems, it is possible to transfer massive amount of energy but at the cost of limited transmission distance. Optical charging systems provide theoretically unlimited transmission range, but they have low efficiency and are susceptible to any obstacles in radiation line.

1 Introduction

Nowadays, electric transport is increasingly being used. While trams and trains have been around for a long time, these types of transport are not able to store electricity. After some time electric transport with power storage devices appeared. But their driving range is not so large, and refueling time is dozens of times longer than models with internal combustion engines. As a result of these problems, it was decided to create wireless charging systems that allow charging electric vehicles without human intervention.

Wireless charging systems are divided into 5 types. Each type has its own sub-types that are used under different circumstances. For example, inductive charging systems [1] are divided into static, dynamic and quasi-dynamic charging systems. All 3 types require a lined power system on motorways and roads, similar to underground cable lines.

P. Chittoor, B. Chokkalingam et al. [2] investigated the available wireless charging systems for unmanned aerial vehicles (UAVs). Drones were originally invented for military purposes, but they have been found to be quite useful for citizens and agriculture, for object surveillance, in farming and delivery of goods over distances. For both electric vehicles and drones, inductive charging methods have become the most common due to their ability to transmit high power, high efficiency, and independence from weather conditions. Attempts at wireless charging systems for drones have been made by different companies [3-5] with an average transmitted power of 200-300 W, the most powerful system is being developed by GET Corporation, which allows 12 kW of power to be transmitted in flight.

* Corresponding author: Shzumeyra@mail.ru

Townsend et al. [6] compared several types of UAVs and their power supplies in their work. It turned out that drones with internal combustion engine are the most efficient, but in terms of environmental safety they are inferior to others.

A. Mahesh et al. [7] in their paper compared all existing electric vehicle charging systems, performed simulation modelling of winding structures for inductive energy transfer, analyzed promising materials in building charging systems and charging infrastructure issues.

A. Ahmad and M. Alam [1] classified existing electric vehicle charging systems according to the power levels of the transferred power: levels 1,2 and 3 for AC and DC charging. They collected data on existing electric vehicles, compared their charging time, travelled distance and battery size. They described the existing problems of dynamic, static and quasi-dynamic charging.

2 Materials and methods

Existing methods of wireless energy transmission fall into two categories: near-field systems (coupled) and far-field systems (radiating). The former operate by magnetic and electric fields, while far-field systems are divided into optical and microwave systems.

Microwave energy transfer operates in the radio frequency range. The magnetron (microwave emitter) is powered by a high voltage DC source. A magnetron is used to create a microwave signal and is powered by a DC source. The generated microwave signal is sent from the antenna and received from the rectenna (receiving antenna). The rectenna consists of a sensor and a rectifier from which the battery is charged.

The optical energy transfer system is carried out using the radiation of light. The system consists of a laser diode that generates light of the required power, a tracer that controls the direction of the beam, a solar panel that receives light from the laser, and a rectifier that powers the load.

The inductive method of wireless power transmission (Fig. 1) is similar to the operation of a weakly coupled transformer, which uses a frequency converter and rectifier as additional equipment. In addition, the AC frequency plays an important role in calculating the air gap thickness. When using frequencies from 3 kHz, the air gap distance reaches up to 20 cm.

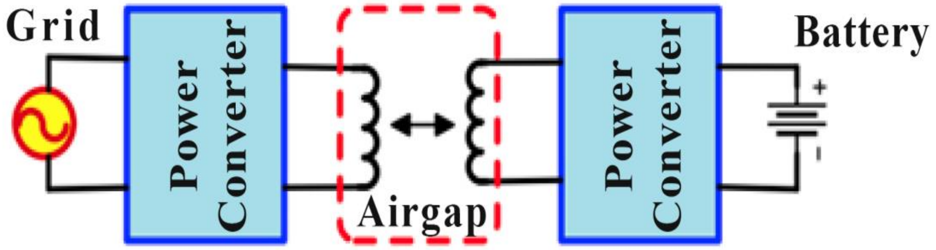


Fig. 1. Structure of the inductive power transfer system, *Source: [7]*

The capacitive charging method allows energy to be transferred through a metallic medium. Unlike the inductive system, the capacitive version can be used at low currents and high voltages. In this case, an inductive element is used on each capacitor, which reduces impedance, improves efficiency and allows easier switching.

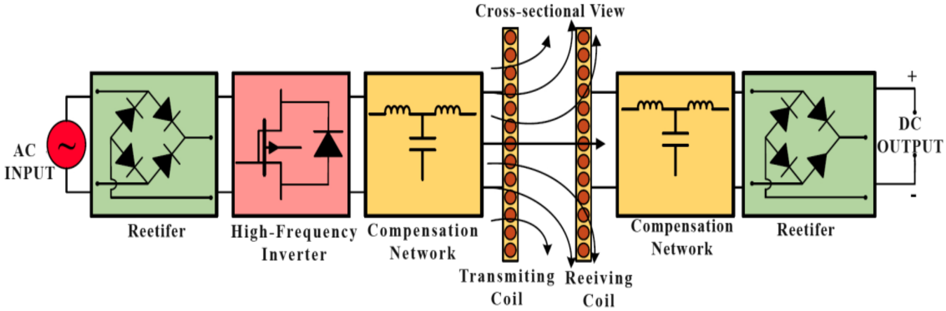


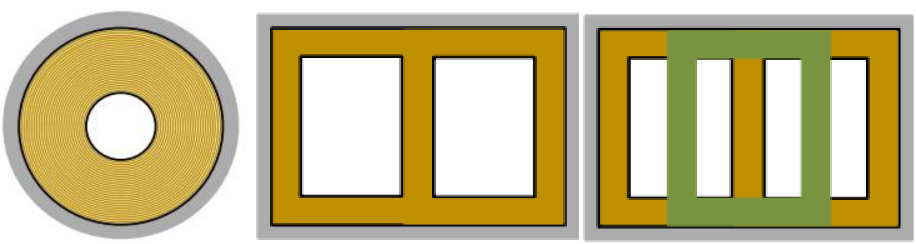
Fig. 2. Diagram of magnetic resonance power transfer system, *Source: [2]*

The magnetic resonance charging system for electric vehicles (Fig. 2) is an improved version of the inductive system. It adds a compensation circuit that forms resonance conditions on the primary and secondary windings.

Magnetic resonant energy transfer systems are divided into resonant-capacitive [8-12] and resonant-inductive [13-16]. At the Massachusetts Institute of Technology, a research group was able to power a 60 W incandescent bulb at a distance of 2 meters without contact [17]. Current research has improved the efficiency of wireless power transfer to 96% at a distance of 20 cm with a power of several kW [18].

In the design of inductive and magnetic resonance charging systems for electric vehicles, 2 types of power plates are used: polarized (PP) and non-polarized (NPP).

Non-polarized plates are panels consisting of a single winding that generates magnetic flux in one direction. Examples are circular (Figure 3a) and rectangular plates. Polarized plates consist of multiple windings that generate magnetic flux in different directions. Examples are DD (Fig. 3b), DDQ (Fig. 3.c) and bipolar plates.



a) b) c)

Fig. 3. Structure of power pads: circular – a; DD – b; DDQ – c., *Source: [19]*

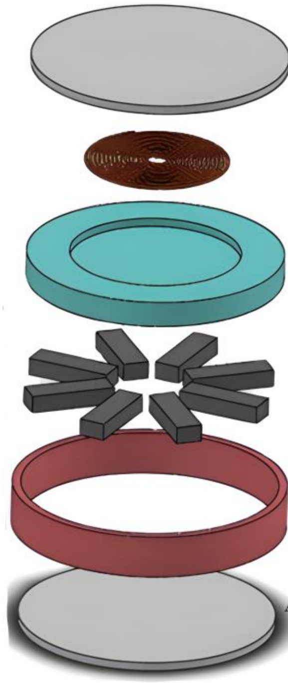


Fig. 4. Exploded view of power pad, *Source: compiled by the authors.*

Daniel Ongayo and Moin Hanif [19] compared the transmitted magnetic flux of circular (Fig. 3a) and rectangular windings and concluded that circular shape performs better than rectangular shape. However, circular windings are not good for dynamic wireless charging because their efficiency is greatly reduced when the primary and secondary windings are offset. To solve this problem, DD, DDQ windings have been developed.

The circular shaped windings (Fig. 4) have a limitation on the size of the air gap. Increasing the air gap thickness by one cm requires a 4-fold increase in the winding diameter, since the ratio of the winding diameter to the magnetic flux path is 1:4 [20].

Table 1. Power pad types and their characteristics

Parameter	Panel Type				
	Round	Rectangular	*DD*	*DDQ*	Bipolar
Transmission distance	Small	Small	Medium	Large	Large
Cost	Cheap	Cheap	Medium	High	Medium
Weight	Light	Light	Light	Medium	Medium
Transmission power	Medium	Medium	High	High	High
Number of windings	1	1	2	3	2
Polarization	No	No	Yes	Yes	Yes
Dissipation flux	High	Medium	Very low	Very low	Very low

Drone charging systems are divided into:

- "Gust soaring" charging technique;
- Charging via solar panels;
- Laser beam charging.

Charging via solar panels (Fig. 5) involves installing photovoltaic cells on the wings of the drone. During the day the solar panels store energy for flight, and at night the charged battery will keep the drone in a state of flight. However, the system is highly dependent on the actual solar radiation and will not be able to fully charge the battery pack in cloudy weather [21].

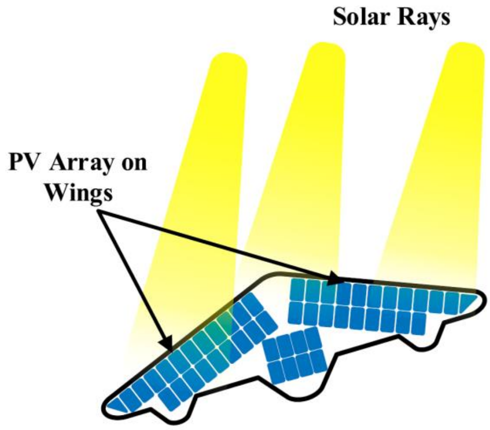


Fig. 5. Wireless charging via solar panels, *Source: compiled by the authors*

Deittert and Richardson created a new charging method called Gust Soaring [22]. The principle of operation is that the drone receives energy from gusts of wind (Fig. 6). The trajectory of the drone is changed so that it catches the rising air flow and moves towards it. The disadvantage of this method is its dependence on wind speed and the possibility of application only for UAVs with rigid wing shape [23].

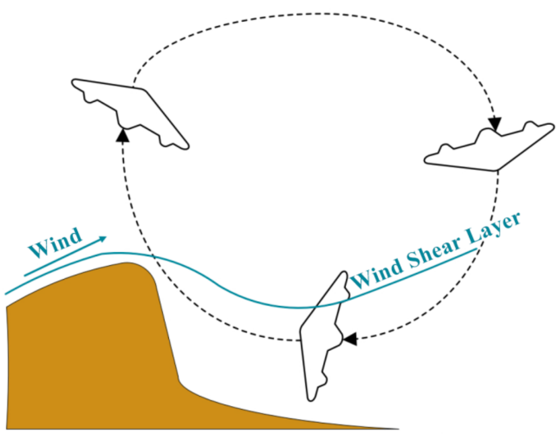


Fig. 6. Gust Soaring UAV charging technique, *Source: [22]*

Laser transmission systems can transmit 2W of energy over a distance of 5 m. This technology is called distributed laser charging (DLC). It operates in the line of sight of the UAV. If there is any obstacle in the path of laser propagation, power transmission is significantly degraded [24]. Microwave wave transmission is theoretically capable of transmitting power over significant distances and operating at 1-6 GHz with 80% efficiency [25-28]. To test the efficiency of the microwave system, an experiment [29-30] was conducted in which a quadcopter was able to stay continuously in the air for 12 hours.

Although the above methods of drone charging are innovative, their application is limited by the type of UAVs and the number of wings they have.

Table 2. Wireless charging types and characteristics

Charging type	Operating frequency	Transmitted energy	Distance
Capacitive	4.2 MHz	3.7 W	0.13 mm
Inductive	22 kHz	100 kW	127mm
Magnetic resonance	60 kHz	818 kW	50 mm
Laser transmission	2.4 GHz	1 W	3.66 m
Microwave transmission	5.8/2.45 GHz	50/4.4 kW	Not limited

Wireless charging systems for electric vehicles are mainly divided into 3 groups: static, dynamic, quasi-dynamic charging. Static charging involves charging electric vehicles in parking lots. Dynamic charging works when vehicles are driving on highways and other roads. Quasi-dynamic charging is activated during moments of short stops on the road, such as at traffic lights, in traffic jams, etc.

The advantage of quasi-dynamic charging is the reduced cost compared to dynamic charging. With quasi-dynamic charging, power plates are installed on each lane of the road in the area in front of the traffic lights. Depending on the location of traffic on the road, the plates are selectively switched on to power the electric vehicle [31]. To calculate the effective number of plates for quasi-stationary charging, the traffic congestion of the road section is analyzed.

3 Results and discussion

There is currently an SAE J2954 standard that defines 4 levels of wireless charging:

- WPT1 with a transmitted power of 3.7 kVA
- WPT2 with a transmitted power of 7.7 kVA;
- WPT3 with a transmitted power of 11 kVA;
- WPT4 with a transmitted power of 22 kVA.

Besides it, other standard setting organizations in this field are IEC with IEC 61980 standard and International Organization for Standardization with ISO-19363 standard.

Existing wireless charging systems differ in terms of frequency used, power, efficiency, air gap dimensions.

Table 3. Applications at different frequencies

Organization	Frequency	Efficiency	Air gap size	Transmitting power
KAIST	20 kHz	71%	1-20 cm	60 kW
Fraunhofer	100 kHz	97%	13.5 cm	22 kW
WiTricity	13.5 MHz	-	5-200 cm	60 W
Tokohu University	360 kHz	75%	0-200 cm	15-18 W
Setsunan University	1.2 GHz	20%-98%	5-25 cm	-

In magnetic resonant energy transmission systems, the magnetic coupler plays a major role. It consists of a primary winding, a secondary winding and a shield. The windings transmit energy through the air, while the shield controls the magnetic flux distributions. Such couplers are commonly used in static wireless charging systems. But the use of classical E-type cores is inefficient for wireless charging of electric vehicles due to their high cost, weight and strong sensitivity to winding displacement, so plate-like winding structures have been developed, which have lower weight and size compared to classical cores.

Table 4. Specifics of existing wireless power transfer systems

Wireless charging technology		Advantages	Disadvantages
Near-field technology	Capacitive	Transmits energy of several kW; Possible to transmit power through metal objects; Cheap due to the use of aluminum plates for power transmission; Maximum air gap thickness of 10 cm	The amount of energy transferred depends on the distance between the plates; Formation of parasitic capacitance; 70-80% efficiency.
	Inductive	Easy to install; Simple control; High efficiency in small air gap; Possibility of two-way power transmission.	Air gap is from mm to cm; Thermal effect in the presence of metallic objects.
	Resonant	The largest transmitted power; Common charging system for electric vehicles; Capable of operating at offset magnetic field lines	Shielding required; Extremely sensitive to objects in the air gap.
Far-field technology	Microwave	Allows transmission of energy over a distance of several kilometers; Allows transmission of several kW of energy.	Difficulty of realization; Low efficiency compared to inductive and capacitive methods;
	Optical	Transmission of several kW of power; Small size of the transmitting device.	20% efficiency; Difficult to control; Significant degradation of performance if there are obstacles in the path of light propagation.

Flat plates [32-35] are designed to minimize the volume and weight of the plate and to be able to operate with any type of winding displacement. In some cases, in addition to the primary and secondary windings, an additional middle winding is added to improve power transfer between the transmitter and the receiver.

Placing the middle winding in the same plane as the primary winding helps to improve the system efficiency under varying load, coupling coefficient and to increase the maximum allowable winding offset. But adding a third winding induces a bifurcation phenomenon, which greatly complicates the design process.

In addition to the classical plate types, hybrid solenoidal [36-41], asymmetrical [42] and DDC plates have been designed to reduce the dissipation loss and increase the allowable bias.

The use of three-phase power system for wireless charging of electric vehicles is more preferable than single-phase power system. It has a larger charging area, allowing a 1.2-meter lane to be powered by 6 plated [43-44].

In dynamic wireless charging, the vehicle is charged while in motion. This technology involves placing the primary windings and auxiliary equipment under the asphalt surface of the road, which is similar to train tracks. One disadvantage of the dynamic charging system is the large energy losses when the electric vehicle is between lanes. The range of transmitted power is between a few watts to kW and depends on the magnetic properties of the windings. To reduce the electromagnetic losses, the underground power supply lane is divided into segments [45-48].

In addition to charging an electric vehicle from the grid, the reverse situation is possible: powering the electric grid from an electric vehicle or a V2G (Vehicle to Grid) system [49]. Such a system can be applied in microgrid system, e.g. in an in-house grid powered by RES. The best application of electric vehicles in V2G is to compensate for power at times of power generation decline from solar panels and wind turbines.

The most popular material used in wireless power transmission systems is copper. Magneto-flat windings are made to improve the conductivity of the coils. Aluminum is commonly used for shielding.

To improve the transmission efficiency, manganese-zinc and nickel-zinc materials are used in inductive systems because of their low losses at high frequencies [50]. They have high magnetic permeability coupled with low electrical conductivity which helps to minimize eddy currents.

The core is made based on magnetic nanoparticles due to which the weight is reduced but the price increases as compared to steel core.

A big obstacle in wireless road power system is the presence of potholes on the road, which can damage the elements of the system. To solve this problem, flexible magnetized concrete has been developed which has low cost and good mechanical performance [51].

In dynamic charging system, the transferred energy is hundreds of kVA because of the high energy capacity of electric vehicle batteries. But semiconductors capable of switching such power are not yet available. The most suitable semiconductor in charging systems is silicon-carbon semiconductor, which has a high switching frequency, but is only able to operate at low powers.

4 Conclusion

In this work, existing wireless charging systems for electric vehicles were reviewed. Wireless technologies are beginning to gain popularity as scientific and practical research due to their reliability, efficiency and minimal dependence on human actions [52].

The main objective of wireless charging systems is to achieve high efficiency compared to wired charging systems. Wireless charging has its limitations such as impact on human activities, issues of fast charging of electric vehicles and cyber security of the systems, economic criterion etc. [53].

Dynamic wireless charging systems are not currently in practice. Most of the research is based at institutes such as KAIST, ORNL, University of Auckland, etc.

A more complex situation is present with the charging of drones as they are quite far from the ground and have a flight duration of up to 30 minutes. Optical and microwave linked charging systems can be used to charge them, but they have low transmitted power, expensive to install, and difficult to work for many consumers.

Wireless charging systems are proving to be safer and more reliable than their wired counterparts.

When designing wireless charging systems, it is necessary to consider the safety of operation, transmitting power, air gap size, efficiency, and the ability to operate at large displacement angles.

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