ATLANTIS PRESS
Advances in Engineering Research, volume 213
Proceedings of the International Scientific and Practical Conference "Young Engineers of the Fuel and Energy Complex: Developing the Energy Agenda of the Future" (EAF 2021)

Critical Review of Wireless Electromagnetic Power Transmission Methods

Ekaterina Frolova[1,*] Nikita Dobroskok[2] Anton Morozov[3]

[1] *Department of Electrical Technology and Converter Engineering, Saint Petersburg Electrotechnical University "LETI", St. Petersburg, Russia*
[2] *Department of Automatic Control Systems, Saint Petersburg Electrotechnical University "LETI", St. Petersburg, Russia*
[3] *RePack AS, Oslo, Norway*
[*] *Corresponding author. Email: eafrolova@stud.etu.ru*

ABSTRACT
The paper presents a comparative analysis of energy transmission methods based on electromagnetism: non-radiative alternating electric, magnetic and electromagnetic fields. The examples of practical realization of the presented technologies are considered. The multi-criteria approach for analyzing the expediency of practical realization of a concrete method of energy transfer including different technical characteristics is offered. The comparative analysis based on the proposed approach shows that the method of resonant inductive energy transfer is the most effective and promising in development.

Keywords: *Wireless energy transfer, Electromagnetism, Resonant inductive coupling, Hybrid wireless coupling.*

1. INTRODUCTION

Due to the current increased interest in studying the negative human impact on the environment, researchers have turned their attention to the contribution of internal combustion engines to total atmospheric emissions. According to the International Energy Agency's 2019 data [1], emissions from cars and other vehicles accounted for 27 % of total global air pollution. In urban areas, according to sources [2–4], emissions from cars and other vehicles can already account for 35 to 70 % of total air pollutant emissions. The solution to this problem has been the development and gradual introduction of safe and environmentally friendly modes of transport based on: hydrogen engines or fuel cells, pneumatic drive, electric drive, etc., into urban infrastructure. Among these, electric-powered vehicles have proven to be the most inexpensive and easy to produce and operate.

Over the past 10 years, the number of land-based electric vehicles in the world has grown: from zero to more than 10 million units [5], which has led to the problem of integrating them into the urban environment. Electrified vehicles use batteries to store energy, which need to be recharged every few hundred kilometers of travel. At the moment, pantographs or cables are mostly used to charge batteries, the use of which is accompanied by a number of problems: relatively low power transfer capacity (resulting in long charging times for high-capacity batteries), in the case of charging cables – high weight, difficulty in organising automated charging. The solution to these problems could be the use of a contactless charging infrastructure.

The task of wireless power transmission (WPT) has interested researchers since Nikola Tesla's first experiments at the end of the 19th century. Since then, many methods of wireless power transmission and their researches have accumulated. This paper will review some of them to identify the most efficient and promising method for industrial applications in high-power devices for wireless power transmission.

2. REVIEW OF EXISTING WIRELESS ENERGY TRANSMISSION METHODS AND EXAMPLES OF THEIR APPLICATION

At present, existing WPT systems can be divided into radiative (energy transmission in optical [6, 7] and microwave [8] range) and non-radiative (energy transmission by magnetic induction [9], magnetic resonance induction [10], electrostatic induction [11] and new hybrid type systems [12]) depending on field type. The classification is given according to foreign sources [13, 14] that set trends in the development of WPT systems. The classification of WPT systems is shown in Figure 1.

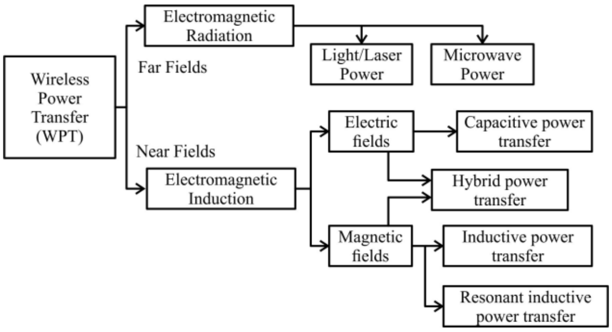

Figure 1 Types of WPT.

The use of radiative fields is limited due to their impact on the environment and human health in particular, so they are not being considered in this article.

Non-radiating technologies include devices operating in the frequency range up to 10 MHz to transmit energy at short (a lot lower the diameter of the receiver and transmitter) and medium distances (up to several lengths of receiver and transmitter diameter), through so-called proximity fields (up to 1/2π of the electromagnetic wave length).

The influence of electromagnetic fields is regulated by the documents of the International Commission on Non-Ionizing Radiation Protection [15, 16].

In general, the operational principle of WPT systems of the type under study can be described using the schematic shown in Figure 2. The core of the system is a transceiver unit, where the transmitting part is connected via auxiliary devices to the power source and the receiver is connected to the power consumer, or load.

The special features of the different WPT systems are not only in the wireless coupling itself, but also in the structure design of these systems. The auxiliary systems include power converters: inverters and rectifiers, as well as reactive energy compensation and impedance matching circuits.

In this article, only the operational principles of the transceiver/receiver devices of the non-radiating WPT systems are considered.

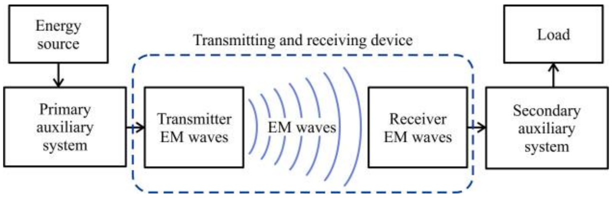

Figure 2 Generalized chart of WPT systems.

2.1. Inductive Power Transmission

Inductive energy transfer uses magnetic field energy. Magnetically coupled coils L1 (primary coil) and L2 (secondary coil) are used as a receiver and transmitter, as shown in Figure 3.

An alternating current is applied to the L1 primary coil, which induces an alternating magnetic field, which acts on the L2 secondary coil. Electromagnetic induction induces an EMF in the second coil, and when the coil is shorted to a load, an induced electric current begins to flow in the circuit.

In general, an inductive WPT system is a transformer, but in transformers the windings are located on a common magnetic core to concentrate and direct most of the magnetic flux, while coils for WPT have no common core, so are loosely coupled [17]. Due to the weak coupling, the efficiency of energy transfer by inductive means is highly dependent on the distance between the coils. As the distance increases, the magnetic field dissipates and more and more of the effective magnetic flux does not reach the receiving coil.

In addition, this method has a low efficiency, which limits its application mainly to low-power devices that are powered from a substantially higher power grid. In such a case, 20–50 % loss of energy for the operation of the power system as a whole is not critical. For example, this charging method is used for smartphones, electric toothbrushes [18], electric razors, medical implantable devices [19], but there are also application concepts for charging electric vehicles [18].

2.2. Resonant Inductive Power Transmission

The resonant coupling method is similar to inductive coupling, but has the important distinction that to increase power transfer, loosely coupled coils are supplemented with capacitance to create an oscillating circuit and produce an increased current when the circuit is tuned to resonance. The resonant current induces a resonant magnetic field, which is captured by a receiving circuit tuned to the same resonant frequency, resulting in more power being transmitted.

There are different structures for realizing resonant coupling between transmitter and receiver: a system with 2 coils as shown in Figure 4a (the capacitive elements that make up the resonant circuit can be in series or in parallel) and a 4-coil system,

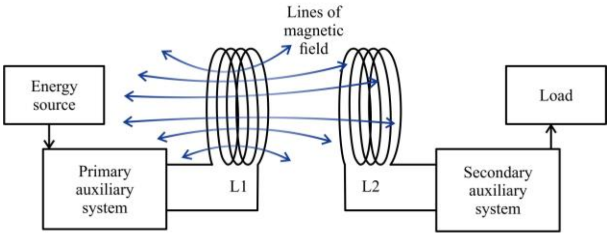

Figure 3 Chart of an inductive WPT.

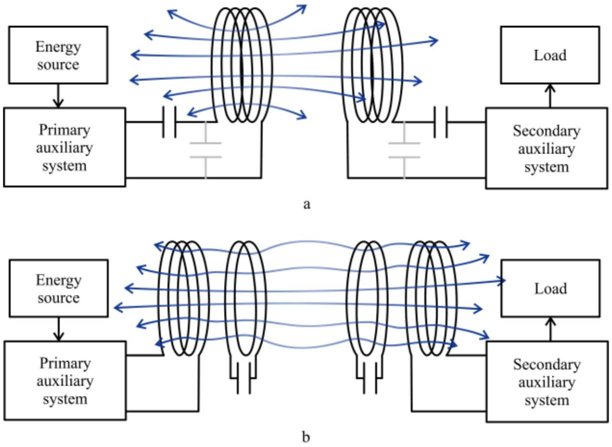

Figure 4 Resonant inductive WPT schematics: a – with two coils, b – with four coils.

as shown in Figure 4b, two of which are coils and the other two are coils that make up the resonant circuit. 4b, two of which are resonant-tuned magnetic field repeater circuits. The latter systems are more efficient because the repeater coils concentrate and direct the magnetic field, which allows increasing the distance between the coils and increasing the transmission efficiency [20].

This method, because of its merits, has found wide application in various fields, from low-power devices (chargers for smartphones, tablets, laptops, etc.) to more powerful ones, examples of which will be discussed below. Wartsila in 2017 introduced a 1MW wireless transmission charger for electrified marine vessels [21]. Currently, the company reports that they have a 2.5 MW wireless charger with a transmission efficiency of 95–97 % [22]. IPT Technology presents projects and concepts for wireless charging of land and marine vessels, as well as solutions for industrial use [23]. The company reports that the efficiency of the proposed systems exceeds 92 % [24]. In 2015, a 1MW real-time wireless power system for high-speed trains with efficiency of 82.7 % was presented based on the same principle [25].

2.3. Capacitive Power Transmission

In contrast to the WPT methods discussed above, the capacitive method uses electric field energy. The system uses metal plate electrodes as the transmitter and receiver, as shown in Figure 5.

High frequency AC voltage is applied to the two primary plates Cs1 and Cs2, and under the action of the electric field according to the laws of electrical induction, a potential appears on the secondary plates Cr1 and Cr2 and a bias current starts flowing in the receiver circuit.

Between the transmitter and receiver plates there is a gap filled with a liquid or gaseous medium, which acts as a dielectric. As in an inductive coupled system, the

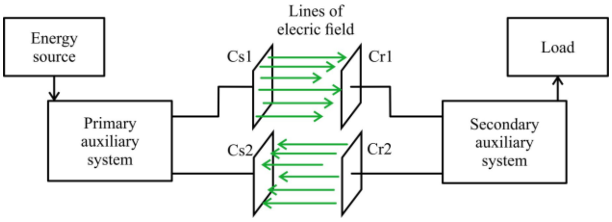

Figure 5 Chart of a capacitive WPT.

efficiency of power transfer is highly dependent on the distance between the transmitter and the receiver [13]. To increase the transmission power density, the voltage on the primary side is raised by an amplifier and then lowered on the secondary side.

The capacitive WPT system can be used over short distances in biomedical devices [26], for charging mobile devices and drones [27, 28]. Moreover, concepts have been developed for applications with more powerful devices such as electric vehicles [29, 30] and all-electric marine vessels [31].

2.4. Hybrid (Inductive and Capacitive) Power Transmission

The latter systems under consideration are called hybrid systems because of their peculiarity: they use both inductive and capacitive coupling for transmission. Research on this topic has only recently started to appear (about the last 5 years) and most review articles on WPT systems do not even consider this method.

In these systems both the coils for inductive coupling and the metal plates for capacitive coupling are placed on the transmitting and receiving sides. These systems have two basic topologies for connecting coils and plates: in series (Figure 6a) and in parallel (Figure 6b).

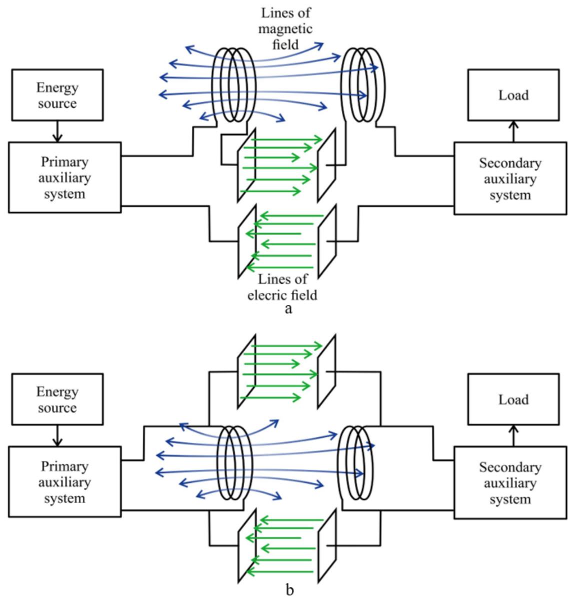

Figure 6 Charts of hybrid WPT structures: a – series topology, b – parallel topology.

Hybrid power transmission systems have several important advantages over other systems:

• with certain design solutions, it is possible to increase the transmitted power density without increasing the transceiver area [32];

• the possibility of more efficient use of capacitive and inductive components used in inductive and capacitive WPT systems to compensate reactive powers and create resonance [33];

• hybrid systems can show greater resistance to axial and transverse displacements due to the different properties of the magnetic and electric fields [34].

To the best of our knowledge, there are currently no practical examples of applications of hybrid WPT systems. However, there are some concepts and developments for applications in power electronics (1 kW energy transfer with 91.9 % efficiency) [35] and railway systems (653 kW energy transfer with 87.7 % efficiency, 8.3 % change in transfer efficiency for displacements from 0 to 270 mm) [36].

3. COMPARATIVE ANALYSIS OF WPT METHODS

The performance of the considered WPT systems are summarized in Table 1 for further comparison.

Table 1. Comparison of non-radiating WPT methods

Comparative values	WPT methods			
	Inductive	Resonant-inductive	Capacitive	Hybrid
Energy transfer	Magnetic field	Magnetic field	Electric field	Magnetic and electric fields
Transmission and receiving devices	Coils	Coils and resonant circuits	Metal plates (electrodes)	Coils and metal plates
Transmission range	Near [37]	Medium [37]	Near [37]	Medium
Transmittable Power	Medium	High	Medium	High
Efficiency	Low	High	Medium	High
Operating Frequencies	Hz-kHz	Hz-MHz	kHz-MHz	kHz-MHz
Direction of field strength flow	Omni-directional	Omni-directional	Uni-directional	Omni-directional and uni-directional
Effective multicast	No	Yes [25]	No	No
Mobility	No	Yes [37, 38]	No	Yes [36]
Hazardous influences	High magnetic field dissipation causes eddy currents in nearby metallic materials	Fairly safe	Bare electrodes under high voltage	Bare electrodes under high voltage
Features	-	Possible to bend the field path (domino effect) [20]	Does not emit electric waves in the absence of a receiving device [31]	Can reduce the eddy currents generated by the magnetic field[a]
Experience of practical implementation	Limited	Wide	Limited	No

[a.] In some designs for hybrid WPT systems, the electric field can limit the magnetic field, thereby reducing its coupling with nearby metals and therefore reducing the parasitic eddy currents in them [12].

The table additionally highlights the characteristics of the WPT methods that have an advantage over the others by a particular criterion, in case one can unambiguously assess the superiority of one method over the other.

Due to the variety of studies and system topologies, the values in the table are presented qualitatively rather than quantitatively.

The criteria include indicators such as:

• range – the distance between the receiver and the transmitter in which the device shows good performance;

• operating frequencies – the range of frequencies used to operate the system;

• direction of power lines – the parameter that influences the occurrence of parasitic flows in the system;

• mobility – dependence of transmission efficiency on axial and transverse displacements;

• experience of practical implementation – possibility to use experience of researchers in development and solution of arising problems, etc.

From the comparison results, it can be seen that two methods are of the highest priority: resonant inductive and hybrid. They both show good performance in terms of power, efficiency, mobility – all the most important characteristics for high power applications. However, in view of the practical implementation experience and processability of WPT systems, the resonant inductive method is currently the most promising for development and implementation in electrical systems. Meanwhile, the hybrid method, despite the lack of experience in practical commercial implementation, has good prospects for the future.

4. CONCLUSION

This paper gives an overview of typical structures of WPT systems based on non-emitting methods, as well as the fields of their practical and commercial applications.

On the basis of a literature review, a list of the main quality indicators (criteria), which can be used to compare the WPT methods, such as: range; amount of transmitted power; efficiency; operating frequency range; possibility and efficiency of multicast power transmission; mobility; safety and experience of practical implementation, is compiled.

Based on the above quality indicators of the WPT methods, it can be concluded that for vehicle charging infrastructure applications, the most promising systems are those based on the resonant-inductive and hybrid method, the latter of which is less preferable for use in the near term due to the need for additional research before commercial implementation. However, some of the advantages cited in the paper indicate the potential for hybrid WPT systems in the future.

AUTHORS' CONTRIBUTIONS

Ekaterina Frolova: corresponding author, conceived of the presented idea, analysed data. Nikita Dobroskok: verified the analytical methods, encouraged E. Frolova to investigate comparative analysis and supervised the findings of this work, co-author. Anton Morozov: contributed to the interpretation of the results, co-author. All authors discussed the results and contributed to the final manuscript.

REFERENCES

[1] IEA (2021), Greenhouse Gas Emissions from Energy: Overview, IEA, Paris https://www.iea.org/reports/greenhouse-gas-emissions-from-energy-overview

[2] J.P. Ivanova, O.O. Ivanova, I.Y. Zorin, Historical role of urban transport in extreme air pollution in the city of Volgograd, in Innovative scientific research in the modern world: Collection of scientific articles based on the materials of the IV International Scientific and Practical Conference, Ufa, 2020, pp. 193-197.

[3] N.V. Krasnokutskaya, Influence of vehicles on the state of atmospheric air in the cities of the Khabarovsk Territory, in Amur Scientific Bulletin No. 4, 2017, pp. 39-43.

[4] A.K. Shlenkin, Impact of road transport on the environment, in In the world of scientific discoveries: materials of the II International student scientific and practical conference, vol. VI, part 4, Ulyanovsk: UlGAU, 2018, pp.199-201.

[5] IEA, Global electric vehicle stock by transport mode, 2010-2020, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-electric-vehicle-stock-by-transport-mode-2010-2020

[6] A. W. S. Putra, H. Kato and T. Maruyama, "Hybrid Optical Wireless Power and Data Transmission System," 2020 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), 2020, pp. 374-376, DOI: https://doi.org/10.1109/WoW47795.2020.9291276

[7] K. Jin and W. Zhou, "Wireless Laser Power Transmission: A Review of Recent Progress," in IEEE Transactions on Power Electronics, vol. 34, no. 4, pp. 3842-3859, April 2019, DOI: https://doi.org/10.1109/TPEL.2018.2853156

[8] K. Li, K. See, W. Koh and J. Zhang, “Design of 2.45 GHz microwave wireless power transfer system for battery charging applications,” 2017 Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL), 2017, pp. 2417-2423, DOI: https://doi.org/10.1109/PIERS-FALL.2017.8293542

[9] M. Debbou and F. Colet, “Inductive wireless power transfer for electric vehicle dynamic charging,” 2016 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), 2016, pp. 118-122, DOI: https://doi.org/10.1109/WoW.2016.7772077

[10] Y. Li, Q. Duan and Y. Huang, “Topology and parameter optimization design for magnetic resonance wireless power transfer system,” 2017 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), 2017, pp. 111-116, DOI: https://doi.org/10.1109/WoW.2017.7959376

[11] K. Yi, J. Jung, B. Lee and Y. You, “Study on a capacitive coupling wireless power transfer with electric vehicle's dielectric substrates for charging an electric vehicle,” 2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), 2017, pp. P.1-P.7, DOI: https://doi.org/10.23919/EPE17ECCEEurope.2017.8099070

[12] X. Chen, S. Yu and X. Yang, “Hybrid wireless power transfer,” IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, 2017, pp. 5348-5352, DOI: https://doi.org/10.1109/IECON.2017.8216926

[13] Rao, T. S. Chandrasekar and K. Geetha. “Categories, Standards and Recent Trends in Wireless Power Transfer: A Survey.” Indian journal of science and technology, vol. 9, iss. 20, pp. 1-11, 2016, DOI: https://doi.org/10.17485/ijst/2016/v9i20/91041

[14] Rao, T. S. Chandrasekar and K. Geetha. “Categories, Standards and Recent Trends in Wireless Power Transfer: A Survey.” Indian journal of science and technology, vol. 9, iss. 20, pp.1-11, 2016, DOI: https://doi.org/10.17485/ijst/2016/v9i20/91041

[15] ICNIRP. Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz). Health Phys 99(6):818- 836; 2010. Pre-print. DOI: https://doi.org/10.1097/HP.0b013e3181f06c86

[16] ICNIRP. Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). Health Phys 118(00):000–000; 2020. Pre-print. DOI: https://doi.org/10.1097/HP.0000000000001210

[17] C. Chen, T. Chu, C. Lin and Z. Jou, “A Study of Loosely Coupled Coils for Wireless Power Transfer,” in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 57, no. 7, pp. 536-540, July 2010, DOI: https://doi.org/10.1109/TCSII.2010.2048403

[18] Valtchev, S., Baikova, E., and Jorge, L, “Electromagnetic field as the wireless transporter of energy,” Facta Universitatis - Series: Electronics and Energetics, vol. 25, no. 3, pp. 171–181, December 2012, DOI: https://doi.org/10.2298/fuee1203171v

[19] Minkyu Je; Myung Hoon Sunwoo, “CHAPTER 04 Wireless Power Transfer Circuits for Biomedical Microsystems,” in Selected Topics in Biomedical Circuits and Systems , River Publishers, 2021, pp.113-142.

[20] Z. Zhang, H. Pang, A. Georgiadis and C. Cecati, “Wireless Power Transfer – An Overview,” in IEEE Transactions on Industrial Electronics, vol. 66, no. 2, pp. 1044-1058, Feb. 2019, DOI: https://doi.org/10.1109/TIE.2018.2835378

[21] G. Guidi, J.A. Suul, F. Jenset and I. Sorfonn, “Wireless Charging for Ships: High-Power Inductive Charging for Battery Electric and Plug-In Hybrid Vessels,” in IEEE Electrification Magazine, vol. 5, no. 3, pp. 22-32, Sept. 2017, DOI: https://doi.org/10.1109/MELE.2017.2718829

[22] Charging – marine vessel charging systems. Wartsila.com. (n.d.). Retrieved November 16, 2021, from https://www.wartsila.com/marine/build/electrical-and-power-systems/shore-power/charging

[23] Your business is our principle for the charging solutions that we develop. IPT Technology. (2020, July 14). Retrieved November 16, 2021, from https://ipt-technology.com/about-us-businesses/

[24] Check our frequently asked questions about wireless power transfer. IPT Technology. (2020, September 8). Retrieved November 16, 2021, from https://ipt-technology.com/faqs-wireless-power-transfer/

[25] J. H. Kim et al., “Development of 1-MW Inductive Power Transfer System for a High-Speed Train,” in IEEE Transactions on Industrial Electronics, vol. 62, no. 10, pp. 6242-6250, Oct. 2015, DOI: https://doi.org/10.1109/TIE.2015.2417122

[26] R. Jegadeesan, K. Agarwal, Y. Guo, S. Yen and N. V. Thakor, “Wireless Power Delivery to Flexible Subcutaneous Implants Using Capacitive Coupling,” in IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 1, pp. 280-292, Jan. 2017, DOI: https://doi.org/10.1109/TMTT.2016.2615623

[27] K. Wang and S. Sanders, “Contactless USB – A capacitive power and bidirectional data transfer system,” 2014 IEEE Applied Power Electronics Conference and Exposition – APEC 2014, 2014, pp. 1342-1347, DOI: https://doi.org/10.1109/APEC.2014.6803481

[28] T.M. Mostafa, A. Muharam and R. Hattori, “Wireless battery charging system for drones via capacitive power transfer,” 2017 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), 2017, pp. 1-6, DOI: https://doi.org/10.1109/WoW.2017.7959357

[29] D.C. LuDOIs and J.K. Reed, “Brushless Mitigation of Bearing Currents in Electric Machines Via Capacitively Coupled Shunting,” in IEEE Transactions on Industry Applications, vol. 51, no. 5, pp. 3783-3790, Sept.-Oct. 2015, DOI: https://doi.org/10.1109/TIA.2015.2434795

[30] F. Lu, H. Zhang and C. Mi, “A Two-Plate Capacitive Wireless Power Transfer System for Electric Vehicle Charging Applications,” in IEEE Transactions on Power Electronics, vol. 33, no. 2, pp. 964-969, Feb. 2018, DOI: https://doi.org/10.1109/TPEL.2017.2735365

[31] H. Zhang and F. Lu, “Feasibility Study of the High-Power Underwater Capacitive Wireless Power Transfer for the Electric Ship Charging Application,” 2019 IEEE Electric Ship Technologies Symposium (ESTS), 2019, pp. 231-235, DOI: https://doi.org/10.1109/ESTS.2019.8847929

[32] X. Chen, S. Yu and X. Yang, “Hybrid wireless power transfer,” IECON 2017 – 43rd Annual Conference of the IEEE Industrial Electronics Society, 2017, pp. 5348-5352, DOI: https://doi.org/10.1109/IECON.2017.8216926

[33] F. Lu, H. Zhang, H. Hofmann and C. C. Mi, “An Inductive and Capacitive Integrated Coupler and Its LCL Compensation Circuit Design for Wireless Power Transfer,” in IEEE Transactions on Industry Applications, vol. 53, no. 5, pp. 4903-4913, Sept.-Oct. 2017, DOI: https://doi.org/10.1109/TIA.2017.2697838

[34] D. Vincent, Phuoc Huynh Sang and S.S. Williamson, “Feasibility study of hybrid inductive and capacitive wireless power transfer for future transportation,” 2017 IEEE Transportation Electrification Conference and Expo (ITEC), 2017, pp. 229-233, DOI: https://doi.org/10.1109/ITEC.2017.7993276

[35] B. Luo, T. Long, R. Mai, R. Dai, Z. He and W.Li, “Analysis and design of hybrid inductive and capacitive wireless power transfer for high-power applications,” IET Power Electronics, vol. 11, Iss. 14, pp. 2263-1170, Oct. 2018, DOI: https://doi.org/10.1049/iet-pel.2018.5279

[36] B. Luo, T. Long, L. Guo, R. Dai, R. Mai and Z. He, “Analysis and Design of Inductive and Capacitive Hybrid Wireless Power Transfer System for Railway Application,” in IEEE Transactions on Industry Applications, vol. 56, no. 3, pp. 3034-3042, May-June 2020, DOI: https://doi.org/10.1109/TIA.2020.2979110

[37] Nguyen, Minh T., Cuong V. Nguyen, Linh H. Truong, Anh M. Le, Toan V. Quyen, Antonino Masaracchia, and Keith A. Teague 2020. “Electromagnetic Field Based WPT Technologies for UAVs: A Comprehensive Survey” *Electronics* 9, no. 3: 461. DOI: https://doi.org/10.3390/electronics9030461

[38] S. Das Barman, T. Ahmed and A. H. Ripon, “Study on efficiency enhancement of resonant coupled wireless power transmission using two-side impedance matching,” 2015 International Conference on Electrical Engineering and Information Communication Technology (ICEEICT), 2015, pp. 1-6, DOI: https://doi.org/10.1109/ICEEICT.2015.7307393