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ELECTROMAGNETIC FIELD AS THE WIRELESS TRANSPORTER OF ENERGY

Stanimir S. Valtchev[1,2], Elena N. Baikova[1], Luis R. Jorge[1]

[1]UNINOVA, UNL, Campus Caparica, Portugal
[2]Faculty of Science and Technology, UNL, Campus Caparica, Portugal

Abstract. *The beginning of the XXI century brought a further significant development in the use of autonomous electrical and electronic equipment. The low consumed power equipment is widely used: laptops, mobile phones, PDA, wireless headphones, implants, razors, toothbrushes etc. The higher power consumption equipment is also starting to work wirelessly, e.g. the intelligent machining complexes, robots, the forklift trucks, and electric or hybrid cars. The desired autonomy and transportability of the equipment requires autonomous energy sources. Until now, almost without exception, the autonomy is guaranteed by electrochemical power with its main problem: to charge, replace and dispose batteries. Engineering world is seeking a non-conventional, wireless transfer of energy, both for charging batteries and directly supplying the equipment. The electromagnetic field is the usual carrier for telecommunicated information. Here an example is shown of electromagnetic transfer of energy, avoiding even the use of ferromagnetic cores.*

Key words: *contactless, wireless, energy, power, transfer*

1. INTRODUCTION

The industrial development nowadays is accompanied by an increased need for energy supply. The increased energy consumption requires science and engineering technology to lead the technological progress simultaneously in two directions: lower global consumption and make available safer and sustainable sources of energy. The depletion of conventional energy sources (oil, gas, coal, etc.) makes those actions urgently necessary. Some important steps have already been taken.

New sources of renewable energy are explored and still more will be in future; more efficient converters of energy and waste recycling facilities are developed; innovative methods of efficient and flexible energy transfer are in development. Those methods include an intensive research in the wireless power transmission.

The wireless power transmission is not a novelty. In the end of the nineteenth century, Dr. Nicola Tesla suggested the idea and experimented for the first time with the wireless transmission of energy. His ideas could not be completely proved experimentally at that time as they required an unachievable level of technology but nowadays many scientists are developing his ideas (or what is known about those ideas).

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Corresponding author: Stanimir S. Valtchev
UNINOVA, UNL, Campus Caparica, Portugal • E-mail: ssv@fct.unl.pt

Wireless energy transfer is defined by its name as a process of transmitting electrical energy from the power source to the load without using wires for connection. Wireless transmission is useful in all cases where interconnecting wires are inconvenient, hazardous, or impossible.

The first basic step in this technology was made by André-Marie Ampère in 1820 (creation of magnetic field by electric current) and all further historical developments are presented in Table 1.

Table 1 History of contactless power transmission

1820	André-Marie Ampere discovered that electric current produces a magnetic field
1831	Michael Faraday discovered electromagnetic induction
1864	James Clerk Maxwell created a mathematical model of electromagnetic radiation
1888	Heinrich Hertz proved experimentally the model of J. C. Maxwell (first radio transmitter)
1893	Nikola Tesla demonstrated the wireless lighting at the World Exposition in Chicago
1926	Hidetsugu Yagi published the structure of the UHF energy transmitting antenna
1944	George I. Babat [10] (URSS) implemented contactless energy transfer to an industrial vehicle by electromagnetic induction
1964	William C. Brown demonstrated a helicopter model moved by energy from the microwave transmitter
1965-1975	William C. Brown demonstrated power transmission of 30 kW at more than 1,6 km mile with 84% efficiency

Basically, there are 2 different methods of wireless energy transmission, defined by the physical phenomena of electromagnetic field propagation: near-field and far-field. Near-field transmissions typically involve application of magnetic field and inductive techniques to transport energy across relatively shorter distances (usually much lower than 1 meter, exceptionally reaching up to a few meters). Far-field electromagnetic transmission methods permit long-range power transfers and typically involve beamed electromagnetic power (lasers, microwave and radio-wave transmissions).

The two methods are best illustrated by examples of their applications for wireless energy transfer. A classification block diagram is shown in Fig.1 presenting main energy transfer applications.

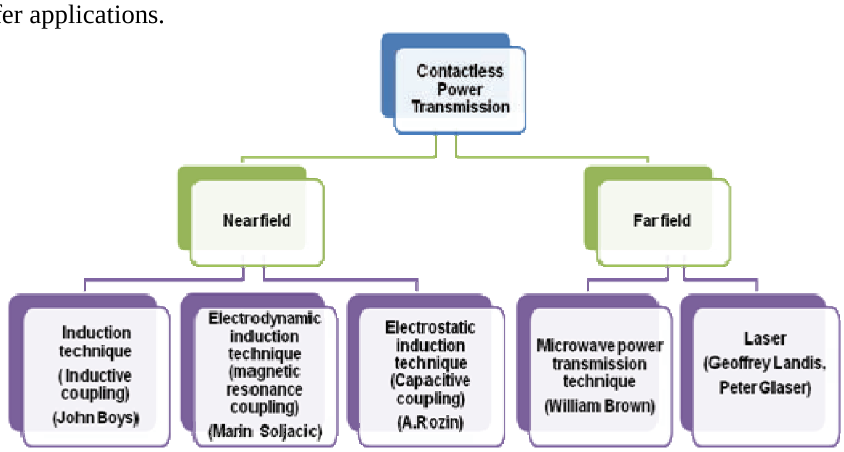


Fig. 1 Classification of the main electromagnetic energy transfer methods

2. NEAR FIELD METHODS

2.1. Induction technique (inductive coupling)

Any contactless transfer energy method based on electromagnetic field, follows the laws of Maxwell, although in case of near field methods the most important is the variation of the magnetic field that induces voltage in a secondary winding. The reason is that the electromagnetic field is always present but the derivative of the magnetic field is disregarded as too low.

The operation of a loosely coupled transformer is the simplest example of induction technique. The inductively coupled coils do not need the Maxwell´s law but the sub-law of magnetic (electromagnetic) induction. Inductive battery chargers of mobile phones or electric toothbrushes are examples of this technique. Even the induction cooker is an example of power transferred by this technique. The main disadvantage of the method is the short range of transfer (usually up to a few centimetres).

Nowadays, the induction coupling energy transfer method is used as conventional technique already made available to the market by many large companies, for example Sony, Fujitsu, Wampfler and Energizer.

The high-frequency transportation system [9] is another example of high-power induction technique - usually a transformer primary winding is laid along the route, and the secondary winding is placed in the car. Energy is transferred from the primary to the secondary winding by electromagnetic field.

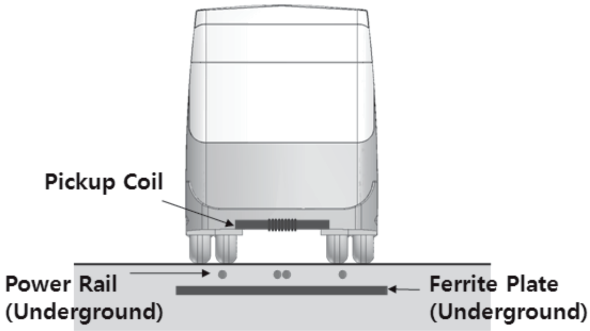
Many engineers and scientists worked on a better contactless energy transfer. There are registered results early in the 20th century from the work of the Soviet electrical engineer George Babat [10], who in 1943 built an electric car supplied by contactless energy transferred from a distance. The vehicle was named "HF automobile". In 1944 he implemented this operation principle in a factory where that type of electric vehicle started to be applied in practice. The motor had a nominal power of 2 kW and ran over asphalt paths under which thin copper tubes were buried. The HF current (50 kHz) in those tubes induced the voltage in the receiver (secondary) winding at a maximum distance of 2-3 dm. After being rectified the energy obtained in the secondary one was used to supply the electric car. The first experiments had the efficiency of only 4% but the results were greatly improved in 1947.

In 1995, John Boys and Grant Covic, of the University of Auckland in New Zealand, developed systems to transfer high amounts of energy across air gaps and proved that power transmission by induction is practicable.

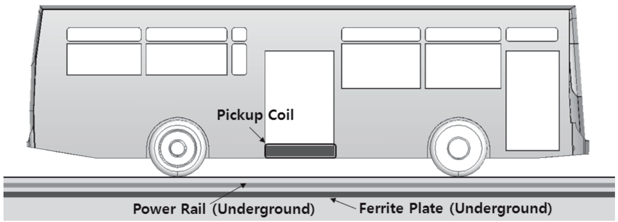
The locomotive company Bombardier Transportation demonstrated the world's first tram, equipped with contactless current collection devices in place of catenaries, named power system PRIMOVE. Cables in the ground created a magnetic field and pick-up coils turned magnetic field into electric current which charged the battery. This power supply is safe, because energy flow is only activated under the tram.

The Korean Advanced Institute of Science and Technology (KAIST) developed the Online Electric Vehicle (OLEV) which is charged by induction from buried inductor loops, placed in specific convenient points, i.e. at the bus stop, road intersection or vehicle parking, transmitting portions of energy for recharge when the vehicle will be situated over that point. The idea is illustrated in Fig. 2 taken from [9].

Similar technologies are already being used in automobile production plants and large warehouse facilities to power remote robotic floors, conveyors and vehicles [3].



(a)



(b)

Fig. 2 OLEV and its power transfer system: (a) side view and (b) front view

2.2. Electrostatic induction technique (capacitive coupling)

The idea of capacitive coupling was patented by A. Rozin in 1998. The energy is transmitted between metallic plates (thus forming one or more capacitors) by the oscillation of a high-frequency electric field. At the receiver side, the battery or other electronic equipment is supplied by the transported high frequency capacitive current (being rectified). Unfortunately, to obtain a reasonable power levels this electric field must achieve too high intensity and this fact limits possible applications.

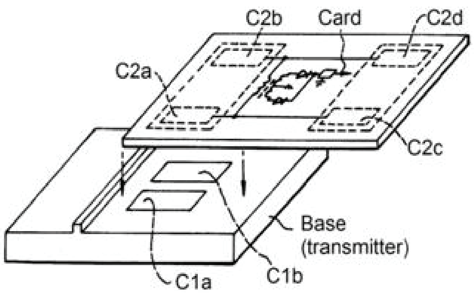


Fig. 3 Capacitive coupling for Smart card

The efficiency of this method is limited by the distance between the transmitter and receiver plates (i.e. the capacitance) and the transmitted power is low. This technique is applicable in sensor supply systems, smart card equipment or in small robots.

2.3. Magnetic resonance coupling

The method of inductive coupling is not efficient when transmitting energy at increased distance and a vast amount of energy is wasted in the form of resistive losses. If the primary and the secondary coils are involved in resonating circuits at the same frequency, significant power can be transferred over that larger distance and the losses are lower. In fact, the resonant method was used by N. Tesla for his energy transfer experiments.

The magnetic resonance coupling occurs when two resonant loops exchange energy through the oscillations of their magnetic fields. In that case all the surrounding impedances have much higher value compared to the good resonant coupling that compensates the positive and negative reactance.

Marin Soljacic with other physicists from Massachusetts Institute of Technology (MIT) proved that a strong resonant magnetic coupling can be used to transfer energy without wires at larger distances, mounting an installation with two tuned up coils at a distance from each other [4], [5].

The experimental design consisted of four copper coils (Fig.4), each connected in a proper resonant loop. The coil A, connected to an AC power supply (9,9 MHz), is a single copper loop of radius 25 cm, that is the power driver connected to the resonant source S. The other coil D, the resonant capture device, was connected magnetically to a 60 watt light bulb. Not only was the light bulb illuminated, but the theoretical predictions of high efficiency over distance were proven experimentally. By placing various objects between the source and capture device, the experiment demonstrated how the magnetic field transfers energy through isolators and around metallic obstacles. It was shown that the power efficiency at this wireless transfer for powering consumer electronics (TV) at relatively long distances (a few meters), can be as high as up to 50% or more.

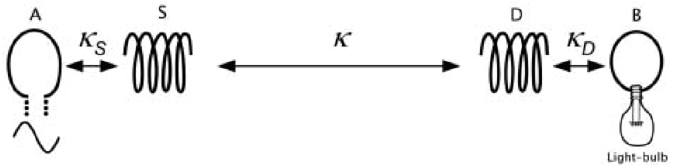


Fig. 4 Simplified schematic diagram of magnetic resonant energy transfer: driver coil A, resonant source S, receiver device resonant coil D, and the bulb (load) B coil

The equations that describe the energy transfer process at the high-frequency magnetic resonance are different from the equations of the inductive coupling at lower frequencies and shorter distance, although both processes apply resonance. For example, the loosely magnetic coupling is described by differential equations with piece-wise constant coefficients [1]. In case of magnetic resonant coupling the equations mostly consider strong resonance and fully shaped sinusoidal currents and voltages as it is shown in [4], [5] and [6]. At the high-frequency of operation some new important parameters appear in the equations, e.g. attenuation factor, characteristic impedance, etc. As the frequency of operation rises, the scattering matrix parameters appear as more convenient [6].

Based on the academic research (e.g. in MIT), industrial companies (e.g. INTEL) are developing practical resonant transmission equipment. In the case of INTEL, it is named Wireless Resonant Energy Link (WREL), and it demonstrates a relatively high efficiency. As the intention of the practical development is to achieve a higher level of transferred energy and power at highest efficiency, for the now existing technology this means applying relatively low frequency of operation. At this frequency some (slower) control methods are applicable that permit sending calculated commands to the switches in real time [2]. The control problems are similar to the usually seen ones in other power converters, but the speed of the processes in the contactless energy transfer technology makes those problems more severe. The classical control of the power converter requires simple, deterministic algorithms, while in the modern technology more sophisticated methods of control are applied. In the contactless energy technology the system elements are in relatively free movement and the structure is changing. In this case the deterministic concept is not easily applicable.

To reach higher power levels, some experiments were done by the group of wireless energy in FCT-UNL (Portugal). The equipment applied in this work is a dielectric welding generator manufactured by APRONEX LTD, Bulgaria. The generator is based on the triode tube ITL 5-1, working in class C, having the following data:

- Frequency band up to 150 MHz;
- CW generated power up to 13 kW;
- Anode voltage up to 7.2 kV;
- Filament voltage/current 6.3 V/65 A.

The generator was experimented in an electromagnetically isolated room, at different frequencies and the result was that the higher resonant frequency guarantees the best energy transfer at a larger distance. In Fig. 5 the generator is shown together with the high-frequency resonant loops, the triode valve (its upper side seen with the two yellow filament wires), the high-voltage oscilloscope probe and the lighted incandescent lamp.

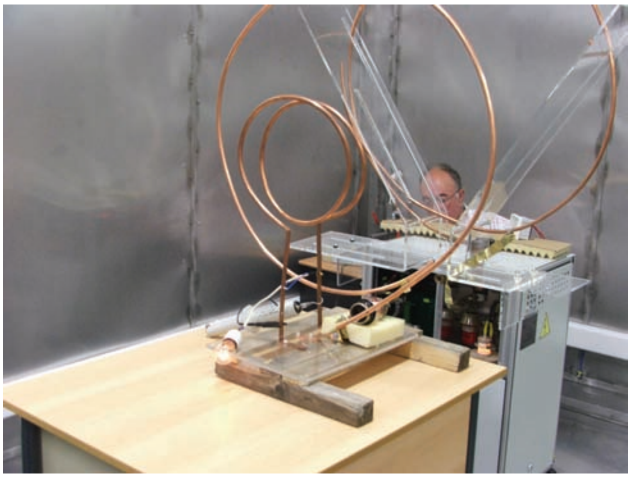


Fig. 5 One of the experiments in the laboratory at 8 MHz frequency and a few kW power

3. Far Field Methods

3.1. Microwave power transmission

According to this method, energy can be transmitted by a well focused microwave energy beam. The complete process consists of three essential parts: a converter from conventional energy to microwave, a transmitting antenna, and a combination of receiving and converting unit called "rectenna". In this method, microwaves are sent at a much larger distance (Fig.6).

One of the pioneers of microwave power transmission was William Brown who in 1964 demonstrated a microwave beam that powered a helicopter model [7].

One possible application of the Wireless Power Transmission via microwave electromagnetic emission is the Solar Power Stations idea [8]. In 1968, Peter Glaser suggested placement of large solar panels on a geostationary orbit to collect and convert sunlight into microwaves, beamed afterwards to a large antenna on the Earth, to be converted into conventional electrical power. In the 70s this thematic was forgotten mainly because of the technological difficulties and the cold war adversary problems.

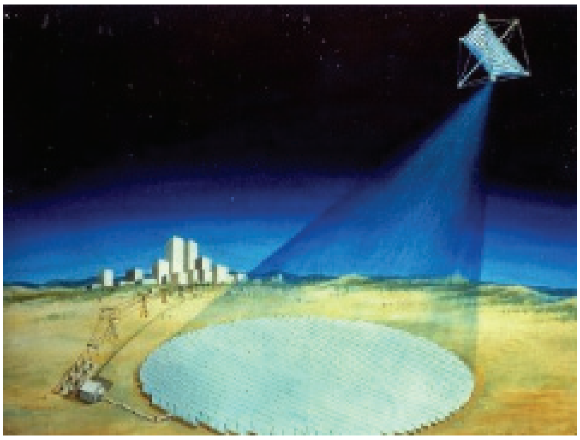


Fig. 6 Project of the solar energy reception (from the space) by rectennas

In recent years the industrial activities in this field are already in revival again. In 2009, the US Corporation Solaren signed a contract with the California Energy Company to supply 200 MW of electric power produced in space from the beginning of 2016.

In comparison to the laser transmission, microwave transmission is more developed, and more efficient, but the diameter of the antenna is to be some kilometres, thus increasing the health and safety risks caused by the focused microwave radiation.

3.2. Laser beamed power transmission

The long-distance wireless power transmission can be realized by converting electricity into laser emission. The laser beam may be focused on a solar panel which transforms it into electricity with an efficiency level of 40-50%. Laser is ideal for power transmission at a distance: it provides a coherent, almost non divergent beam with high energy density, thus allowing smaller diameter of the antenna.

Unfortunately, certain disadvantages reduce the benefit of laser: the imperfection of existing technologies leads to the loss of the most of energy during the transformation of the laser beam into electric power. Before making the method effective, more efficient solar cells must be developed. Another significant drawback of laser is safety: the danger of hitting any object in the area of the beam. On the other hand, laser energy transmission allows much higher energy densities, a narrower focus of the beam and smaller emission and receiver diameters in comparison with microwave energy transmission.

Laser beaming is already used successfully in models and prototypes developed by specialized companies, e.g. LaserMotive. This Seattle-based company developed a space elevator prototype supplied by a laser beam (about 1 kW) to lift 50 kg (Fig.7).

Fig. 7 Prototype of space elevator (LaserMotive)

In September 2003 with a laser beam centered on its panel of photovoltaic cells a model plane made the first flight of an aircraft powered by an infrared laser beam inside a building at NASA Marshall.

4. BIOLOGICAL IMPACT OF WPT

Strong high-frequency magnetic fields are a source of electromagnetic radiation and may be harmful. Although the developers claim that the technology is safe for humans, no one can predict the impact on human health over time. Many scientific studies have investigated possible health effects of electromagnetic radiations.

The human body is composed of conductive tissues (e.g. neural) and fluids (blood, lymph, intercellular fluid). In view of this circumstances human body as a whole as well as its individual parts represent resonators and hence antennas.

Human body may oscillate with the electromagnetic radiation in resonance with the wavelength of the transmitted energy and the resonance may occur related to the whole wavelength or a fraction of it. In Fig.8 a human body of 1,7 meters height is presented as a resonator (antenna) for several frequencies: 180 MHz, 45 MHz and 11 MHz.

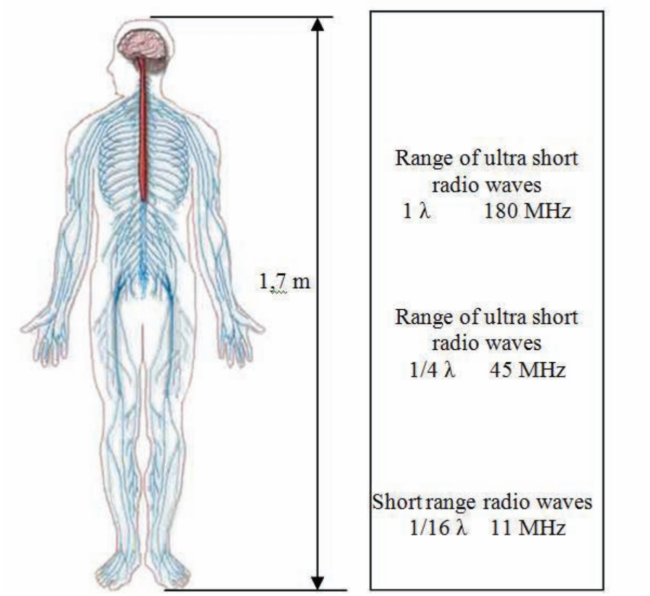


Fig. 8 Resonant frequencies of the human body (for stature of 1.7 m)

The same resonant processes may apply to different (shorter) parts of the body, shown in Fig.8. In that case, the electromagnetic field may influence biological structures and their functions, e.g. nerves, muscle fibres, etc. The consequence of this influence may be heart rhythm disturbances, muscle spasms, etc.

Common symptoms may be expected as:

- Weaken concentration;
- Headaches;
- Weakness;
- Chronic fatigue;
- Loss of power;
- Reduced sexual potency, etc.

Symptoms of the nervous system:

- Functional disorders of the central and autonomic nervous systems;
- Changes in the electroencephalogram;
- Neurasthenic manifestations.

Symptoms of the cardiovascular system:

- Pulse instability;
- Instability of blood pressure;
- Cardiovascular disorders.

More research is essential to study those possible health effects.

5. Comparison between the Existing Methods

The comparison is presented in Table 2 based on the available knowledge (publications). It is still not known which solution will be adopted for future development, but if the highest levels of power should be transferred then the directional (beam) methods are more likely to be used (Microwave power transmission). This method is capable to transport energy in gigawatts power levels.

At the lowest power levels the high quality factor (Q) strong resonant coupling is more proper, probably it is not possible to apply ferromagnetic materials and thus the prediction is to operate at high frequencies. This is probably the technology for the future medical implants.

Table 2 Comparison between the existing methods

	Inductive coupling	Magnetic resonance coupling	Capacitive coupling	Microwave power transmission	Laser
Received power	several W to hundreds of kW	hundreds of W	up to 1 W	up to tens of kW	expected MW
Operating distance	up to several cm	up to several m	up to several mm	up to tens of km	up to tens of km
Operating frequency	several kHz to tens of kHz	several MHz	up to MHz	up to 300 GHz	Higher than 1 THz
Convenience	acceptable level	high level	acceptable level	high level	high level
Efficiency	highest	high	low	medium	medium
Biological Impact	minor	medium	minor	significant	significant

The classical magnetic coupling will probably remain for the battery charging and applications in industry. The inductive coupling is characterized by high efficiency and minor biological impact, but it is applicable over very short distance.

Each topology has its preferred application and probably all those methods of energy transfer will exist in future.

6. Conclusion

The wireless transfer of energy is considered one of the most attractive new technologies and does have its place in future. Although this technology is still not widely applied for high level of electric power and large distance, there are signs that the research in this direction is intensive and has never stopped.

Comparing the wireless energy transfer to the classical electrical energy transport by high voltage lines, a contactless technology is capable not only of cuting down the construction expenses of power lines, but also of providing unconventional solutions, e.g. capable of switching the highest power supplied to one point of the Earth to another point on the Earth in the shortest possible time. All this will save money, time, material, and natural resources.

REFERENCES

[1] S. Valtchev, B. Borges, K. Brandisky and J. Ben Klaassens, "Resonant Contactless Energy Transfer With Improved Efficiency", *IEEE Transactions on Power Electronics*, vol. 24, no. 3, pp. 685-699, 2009.

[2] S. Valtchev and Svilen Valtchev, "Improved strategy for an Instantaneous Super-Resonant Converter Regulation", *Proceedings of 12th International Conf. OPTIM 2010*, Romania, 2010, pp. 631-638.

[3] J. T. Boys, G. Covic and A. Green, "Stability and control of inductively coupled power transfer systems", *IEE Proc., Electr. Power Appl.*, vol. 147, no. 1, pp. 37–43, 2000.

[4] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher and M. Soljacic, "Wireless Power Transfer via Strongly Coupled Magnetic Resonances", *Science Express*, vol. 317. no. 5834, pp. 83 – 86, 2007.

[5] A. Karalis A., J.D. Joannopoulos and M. Soljacic, "Efficient wireless non-radiative mid-range energy transfer", *Annals of Physics*, vol. 323, no. 1, pp 34-48, 2008.

[6] T. Imura, H. Okabe and Y. Hori, "Basic experimental study on helical antennas of wireless power transfer for Electric Vehicles by using magnetic resonant couplings", *IEEE Vehicle Power and Propulsion Conference VPPC '09*, 2009.

[7] W. Brown, "The History of Power Transmission by Radio Waves", *IEEE Transaction on Microwave Theory and Techniques*, vol. MTT-32, no. 9, 1984.

[8] G. Landis, "A super synchronous solar power", *Presented at SPS-97: Space &electric power for humanity, Montreal*, Canada, 1997, pp. 24-25.

[9] A. Seungyoung, J. Pak, T. Song, H. Lee, J. Byun, D. Kang, C.-S. Choi, Y. Chun, C. Rim, J.-H. Yim, D.-H. Cho and J. Kim, "Low Frequency Electromagnetic Field Reduction Techniques for the On-Line Electric Vehicle (OLEV)", *IEEE Electromagnetic Compatibility Symposium*, 978-1-4244-6307-7/10, Daejeon, pp. 625-630, 2010.

[10] G. I. Babat, "Electrodeless discharges and some allied problems", *Journal of the Institution of Electrical Engineers - Part III: Radio and Communication Engineering*, vol. 94, pp. 27-37, 1947.