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ORIGINAL PAPER

An Application of a Wireless Power Transfer at Low Frequency Range

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Abstract

In this study, a low frequency wireless power transfer (LFWPT) device has been designed and implemented. The aim of investigation of low frequency system is to eliminate the un-healthy situation due to non-ionized radiation of the high frequency regimes. The transmitter uses a special winding to transmit the electromagnetic signals to the environment, especially for a few centimeters distance. The receiver winding, which is the same with the transmitter winding catches the signal and stores it in capacitor. The system uses maximum 17,649 Hz to transmit the signal, that is fairly low compared to the other studies in the literature. A DC-AC inverter is used to obtain high frequency signals for the transmitter circuit. The experiments have proven that the receiving antenna can get 1 V amplitude from the transmitted peak-to-peak amplitude of 140 V at the operation frequency.

Keywords Wireless power transfer · Power · IGBT · Low frequency

Introduction

Electrical form of energy has a wide application area in our daily-life such as transportation, medicine, agriculture, communication, industry, illumination. Almost all devices use the electricity, thereby the electrical devices require a power transmission and that transmission is mainly made from the network connection via a cable [1–3]. Due to Joule heating and damages on the cables, there may be accidents in the houses and industrıes in addition to the cable costs. Therefore, to eliminate these artifacts, there exist a continuous trend to transmit the electrical power without a cable or any other conducting material between the network connection point and device. This goal has caused many attempts to design and implement different wireless power transmitting systems, which are mainly made for frequencies higher than 100 kHz, however such a high frequency regime for the transmission causes a non-ionizing electromagnetic pollution [4]. That is especially a problem for health. According to the international standards, there exist a number of available regulations on the thresholds of the non-ionizing radiation [5]. To fulfill these regulations, the main task is to make energy transmission at low frequency band. The present work mainly focuses on this idea to test the achievements of low frequency transmission [6, 7].

According to the literature, there exist many applications on wireless transfer systems [8–11]. The main idea has become the transmission of electricity in near distance economically and efficiently. Strictly speaking, the transmission is provided between a transmitter and receiver by using a resonance frequency. For instance, a three-phase ac voltage can be converted to a dc voltage via a rectifier first, then this dc voltage can be converted to a higher frequency ac voltage and sent to an antenna. The receiver antenna would get the signal at the identical resonant frequency. Afterwards, it can be stored into a capacitor or a battery via a dc conversion.

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Table 1 Components used in simulation

Item no	Item	Description
1	Transmitter Inductor	0.7 mH
2	Receiver Inductor	0.7 mH
3	Capacitor	900 µF
4	Resonance frequency (Hz)	17,649

Historically, Tesla invented some different wireless power transmission components at the beginning of 1900 [12]. After one century, the wireless power transmission gets much interest due to the raising importance of electricity in all sectors from mobile to electric vehicles [13]. For instance, wireless chargers are nothing else than the application of wireless power transfer. Indeed, the transfer is possible for short distances as for cellphones [14–17]. Another issue related to the power transfer is the antenna structure. The antennas which operate well for information, cannot be used for transferring energy. Since their modulation is capable to send or receive the information. However, the large amount of energy is lost in the air media. Apart from such antenna structures, multi-directional antennas with directed radiation modes can be used for the wireless transfer, efficiently.

In many recent applications such as laptops, mobile phones, etc., very close distances with low powers (i.e. mW) are encountered [18, 19]. Besides, a more efficient, radiation-free and medium distance wireless solutions are focused with long life oscillatory electromagnetic modes.

The methodology of power transfer is related to the phenomena of resonant coupled circuits principle. This principle indeed provides a connection between two circuits, which are not far away from each other. For medium and long distances, the nature of these couplings has not been fully understood and that is an on-going work. For instance, the works in MIT proved that the power can be transferred with this principle in 2007. The power P=60 W was transferred in a wireless manner to 2 meters away with 60% efficiency [14–20]. However, the efficiency still stays as main problem.

If this principle can be applied for larger scales in power and distance, there will be so many advantages such as;

1) High voltage transmission lines will be removed.
2) The connection between the electrical plants will be easier globally.
3) High expenditures on transmission lines and related components will be removed.
4) Freedom of preferences for transmitting institution and clients will be obtained.
5) The electricity cost for the clients will decrease.
6) The power will be delivered via air media to the harsh environmental locations easily.
7) There will be no unplanned electricity cuttings and short circuits caused by transmission lines and transformers.
8) The forest fires caused by transmission lines will be prevented.
9) The power cable accidents involved by the workers and technicians will be prevented.

In spite of all mentioned advantages, some disadvantages of wireless power transfer like high power loss, non-directionality, inefficiency for longer distances are inevitable for this type of power transfer. In the present work, initially the wireless power transmission systems are briefly introduced. Then, a theoretical study with Matlab application will be presented in Sec. 3. The novel part of the work is to use low frequency circuit elements to generate and recover the power signal to our knowledge. The experiments results and main findings are given in Section 4. Finally, the paper ends with a conclusions section.

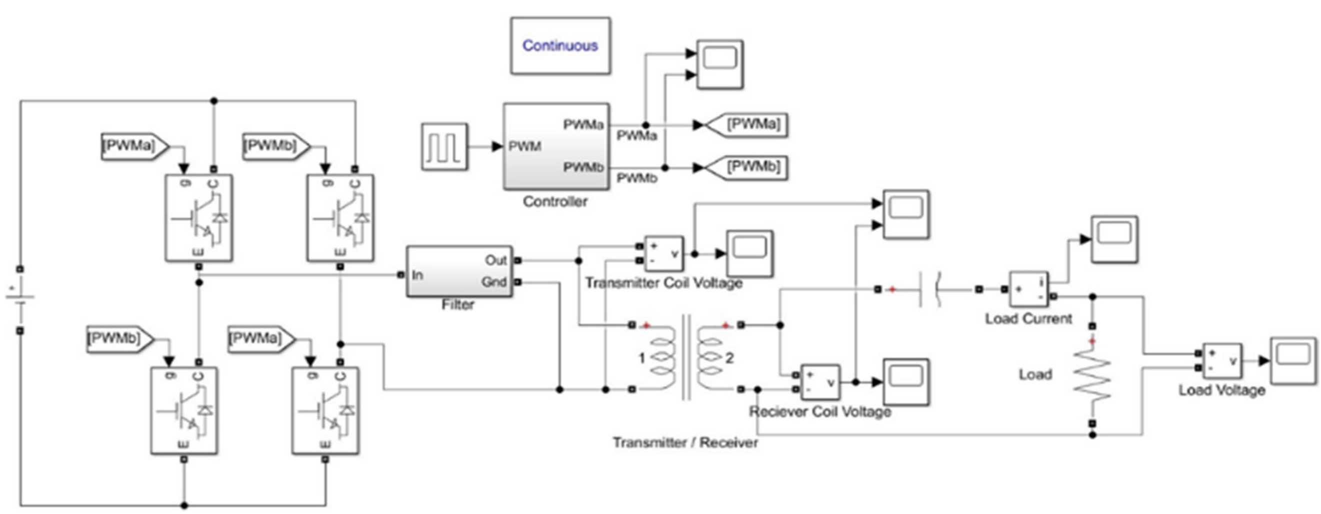
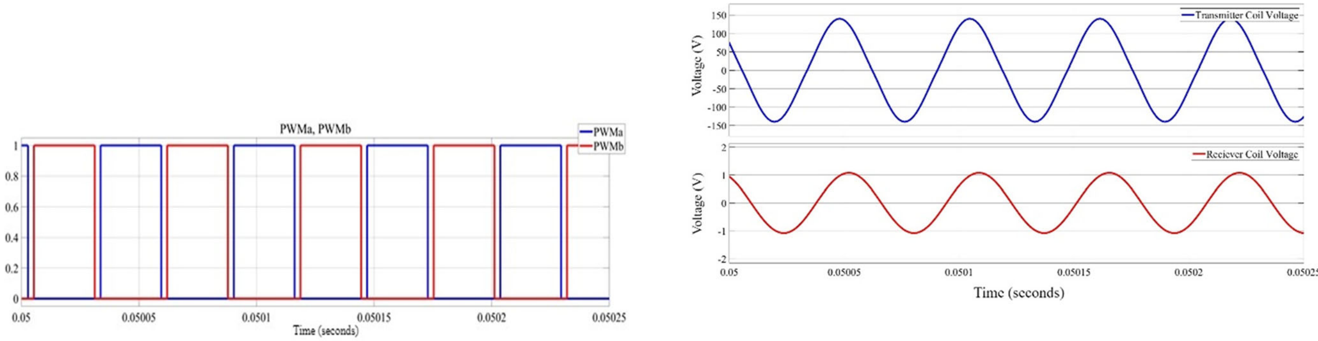
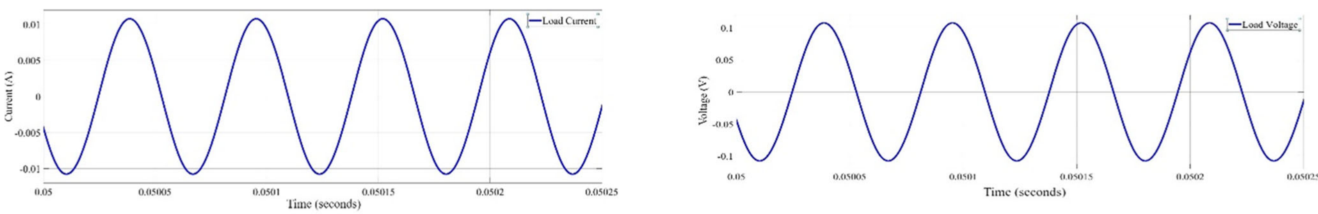


Fig. 1 System simulated in MatLab Simulink



(a) (b)

Fig. 2 **a** PWM signals of single phase full bridge inverter, **b** transmitter and receiver antenna voltage waveforms



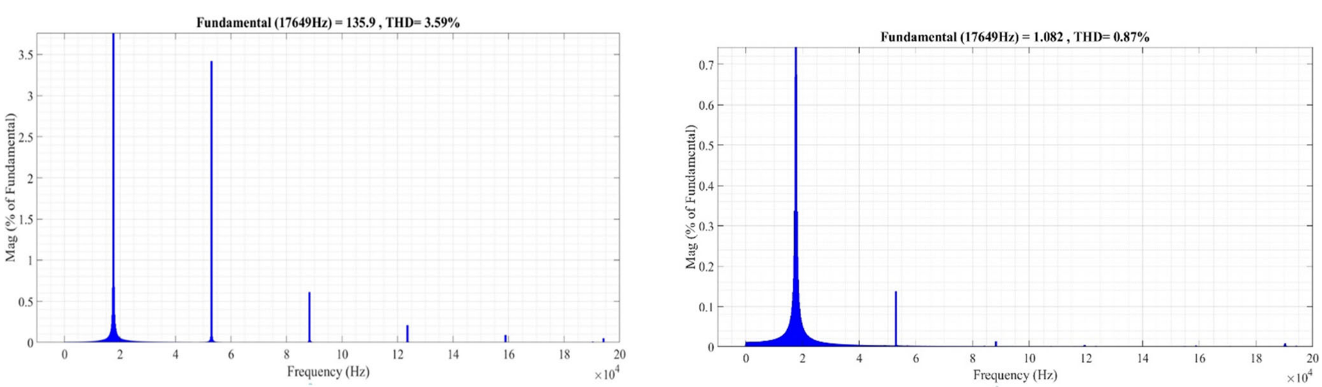
(a) (b)

Fig. 3 **a** Load current and **b** voltage waveforms

Wireless Power Transmission

In recent years, wireless power transmission systems have become so important for human beings, especially for charging the electrical vehicles and mobile phones. For electrical vehicles, wireless power transmission instead of charging with a power cable, has become more secure for drivers and passengers since most of the batteries are charged in a short time with high amounts of charge capacity. Since the inductive wireless power transmission is mostly suitable for such a charging application, many of the literature studies use the inductive systems as in Refs. [21, 22]. In the inductive unit, there exist two types of antennas: Circular coil system with a centered core and a toroidal coil system.

Another important issue is to decrease the charging time, since the customers prefer the short charging durations in the products. However, the smaller coils can cause some thermal problems. Therefore, serial connected resonant capacitors are preferred in many circuits. In Ref. [23], a 7 kW wireless system was explored and the effects of coil geometries, core losses and connection coefficients were examined. The efficiency was also found for these geometries. Kudo and co-



(a) (b)

Fig. 4 The THD values of **a** transmitter antenna voltage and **b** receiver antenna voltage

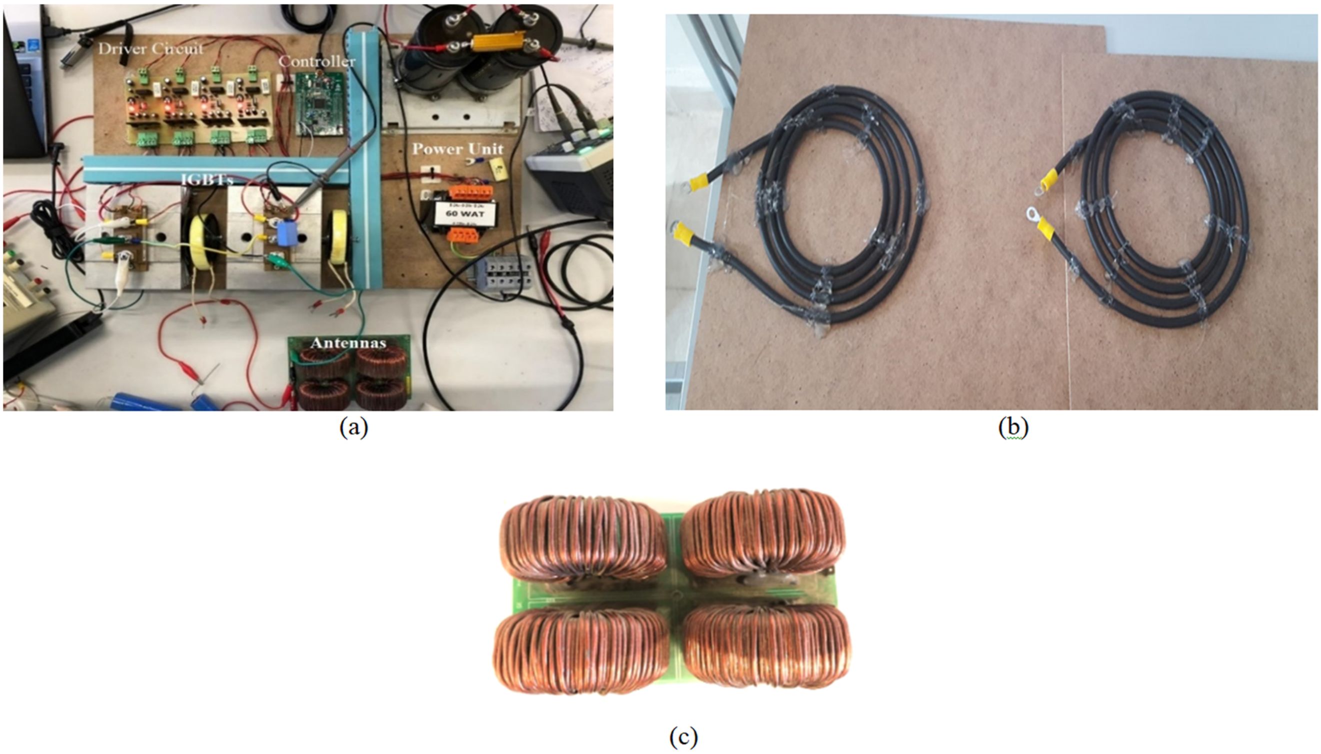


Fig. 5 **a** The overall experimental setup, **b** Spiral type transmitter and receiver antennas (Antenna A), **c** Toroidal transmitter and receiver antennas (Antenna B)

workers [24] suggested a more efficient system with lower voltage scales and higher electrical charge amounts, thereby a double layer capacitor system with low voltage and high currents which was considered for low electrical load.

In the literature, changing the full-bridge rectifier with a current doubler rectifier is not an appropriate selection, because the inductors used in the current doubler rectifier are physically bigger and heavier than the diodes of full-bridge rectifiers. Apart from that, current doubler rectifiers can be preferred especially for high power systems due to the fact that the secondary coils are heavier than the ones in the rectifier. In another work, Chigira, et al., [25] practiced a current doubler rectifier system and found that the solenoidal coils exhibit better performance than the circular ones in the directional power transmission. They also offered a new H-shaped coil system and tested that in their work.

Table 2 Experimental Components

Item no	Item	Description
1	Diodes	DSEI 12–20
2	IGBT Switches	2MBI100U-4A
3	Transmitter Inductor	0.7 mH
4	Receiver Inductor	0.7 mH
5	Capacitors	0.2 μF
6	Resonance frequency	13.33 kHz

Simulations

The simulations are entirely performed in MatLab package program. In the simulations, a dc-ac converter and controller units have been designed for the energy transmitter. An appropriate PWM signal is applied into the converter via a STM32F407VG Controller.

The block diagram of overall system simulated in MatLab Simulink is given in Fig.1. Components used in simulation program are presented in Table 1.

Figure 2(a) gives a sample of pulse waveforms with a periodic output. The antenna's transmitter and receiver voltage waveforms are given by Fig. 2(b). As it is obvious from the signals, they show ideal sinusoidal signal characteristic with low THD values. Load current and voltage waveforms are shown in Fig. 3(a, b).

At the terminals of receiver unit, an electrical load has been connected (Fig. 1). The current is found as 11 mA (Fig. 3(a)). In the case of voltage, amplitude is observed as 0.11 V (Fig. 3(b)). It is obvious from Fig. 3 that the output over the load is ideal sinusoidal, too.

The maximum THD values of the voltages from the transmitter and receiver antennas are given in Fig. 4(a, b). It is clear

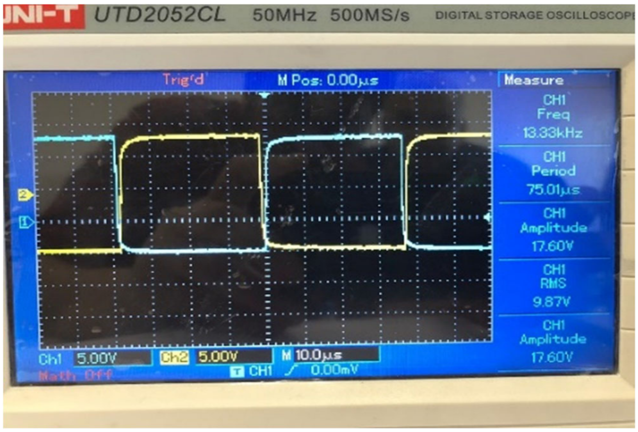


Fig. 6 IGBTs output signals

that the THD values differ for the transmitting and receiving units. Strictly speaking, the lowest THD value is obtained at the receiver antenna unit with 0.87%. However, the THD value increases for the transmitting antenna unit due to the switching process of IGBTs and transmitting unit filter. The THD value of the transmitter antenna voltage is measured as 3.59%, which is appropriate for such low frequency wireless power transfer applications. Note also that both THD plots indicate the superharmonics of the fundamental frequency of 17,649 Hz. For the transmitting antenna, almost four superharmonics appear, however, in the case of receiver antenna, only two superharmonics exist due to the low THD value.

Experimental Results and Discussion

The experimental setup of the work is given in Fig. 5(a). The upper left corner is the controller unit and the lower left corner shows the IGBT units for low frequency excitation. Lower right corner is the feeding transformers of controllers. The energy storage is shown in upper right corner with capacitors.

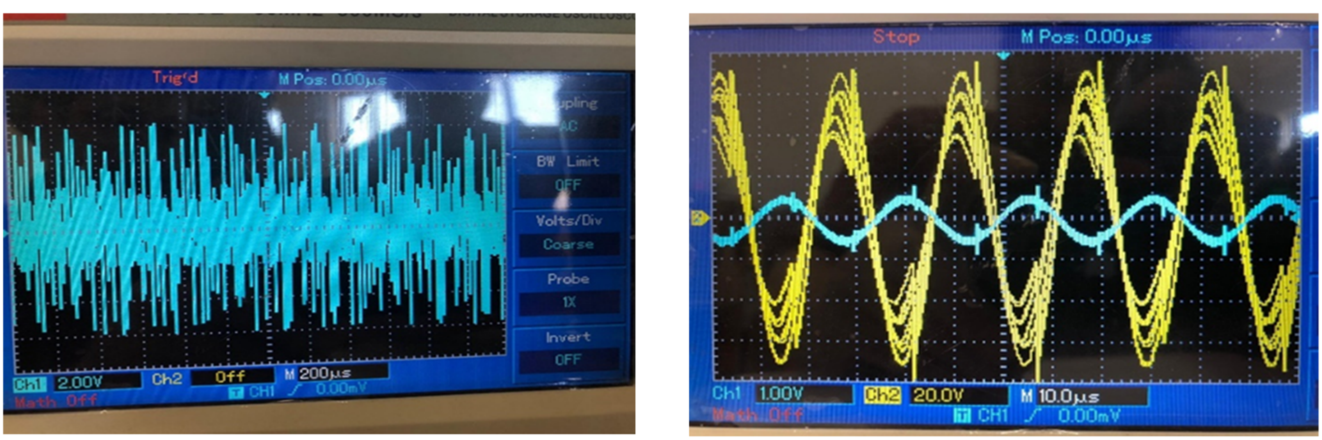
In the experimental work, the diodes DSEI 12–20 are used. 2MBI100U-4A IGBTs are used for the resonance frequency adjustment and dc-ac conversion in converter. The output signal of the converter has been directly applied into the antenna. While Fig. 5(b) gives the larger form of controller unit, Figs. 5(b, c) show the antenna types, which are used in this work. Components used in experiments are given in Table 2.

During the operation of the power transmitter, received output signals of IGBTs for the operation of circuit are presented in Fig. 6.

Figure 7(a) gives the signal from the transmitter circuit antenna A. The signal is highly affected by the radio frequencies at the surrounding media. Note that it is in the order of 10 Volts, therefore, it can be said that the spiral type antennas are not appropriate for such low frequency applications (i.e. 13,330 Hz). However, Antenna B (i.e. toroidal antenna) gives more clear results as shown in Fig. 7(b) with 2 cm distance, the signal from the transmitting circuit decreases to 1.2 V in amplitude from the value of 140 V.

Conclusions

A wireless power transfer system has been designed and implemented in this paper. The system operates at 17,649 Hz in simulated model, which is a low frequency compared to the other microwave frequency wireless power transferring systems theoretically. The experimental structure is also constructed in this work. The experimental setup enables transmission of power at lower frequencies like 13,330 Hz. Such low frequency values are in radio-frequency limits and produce lower non-ionizing radiation compared to the microwave frequencies. According to the simulation results, the transmitter and receiver voltage waveforms are sinosidal with low THD values. On the other hand, for experimental work, two types of antennas have been tested and it is found that unlike simulation study results, spiral type antenna produces highly



(a) (b)

Fig. 7 **a** Transmitted signal from the Antenna A, **b** Transmitted and received signals from the Antenna B with 2 cm distance harmonic output and it is not appropriate for such purposes. Meanwhile, toroidal type antennas have exhibited a better result, that is one of the innovative findings of the present work. Since the frequency is low, the signal decays tremendously at the receiving circuit. Strictly speaking, 1.2 V is obtained in the receiver circuit while 140 V is transmitted. Thus high amount of signal is lost in the media.

References

1. Mahariq I, Berjozkina S (2019) Experimental realization of electromigration at high power for copper wires. J Energy Syst 3(4):158–167. https://doi.org/10.30521/jes.616982
2. Dursun B, Kurt E, Tekerek M (2019) A power circuit design for the poloidal field coils in a torus shaped plasma system. J Energy Syst 3(3):123–128. https://doi.org/10.30521/jes.609667
3. Feng W et al (2020) Joint 3D trajectory design and time allocation for UAV-enabled wireless power transfer networks, IEEE Trans. on Vehicular Tech. https://doi.org/10.1109/TVT.2020.2972133
4. Frah M, Belyaev V (2019) Parameters of electromagnetic pollution from different sources and their hazard impact. J Physics: Conference Series 1309:012013. https://doi.org/10.1088/1742-6596/1309/1/012013
5. Syaza SKF, Umar R, Sabri N, Kamarudin MKA, Hassan A, Juahir H (2018) Non-ionizing radiation as threat in daily life. J Fund Applied Sci 9:308. https://doi.org/10.4314/jfas.v9i2s.21I
6. Mohammed SS, Ramasamy K, Shanmuganantham T (2010) Wireless Power Transmission - A Next Generation Power Transmission System. Int J Computer Appl 1. https://doi.org/10.5120/274-434
7. Inoue R, Miyagi D, Tsuda M, Matsuki H (2017) High-efficiency transmission of a wireless power transmission system for low- frequency using REBCO double-pancake coils. In IEEE TransAppl Superc 27(1):1–6. Art no. 5400106. https://doi.org/10.1109/TASC.2016.2629263
8. Shin S et al (2013) Wireless power transfer system for high power application and a method of segmentation. IEEE Wireless Power Transfer (WPT), Perugia, pp 76–78
9. Minnaert B, Stevens N (2018) Maximizing the power transfer for a mixed inductive and capacitive wireless power transfer system. IEEE Wireless Power Transfer Conference (WPTC), Montreal, pp 1–4
10. Bechtold T, Acevedo JAP, Hohlfeld D (2017) Compact model of a wireless power transfer system. IEEE Wireless Power Transfer Conference (WPTC), Taipei, pp 1–3
11. Tan L, Pan S, Huang X, Xu C (2017) System optimization for wireless power transfer system with double transmitters. IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), Chongqing, pp 1–3
12. Valone T (2017) Geoengineering Tesla's Wireless Power Transmission. Extra Ordinary Sci Tech:31–43
13. Brown S, Pyke D, Steenhof P (2010) Electric vehicles: the role and importance of standards in an emerging market. Energy Policy 38: 3797–3806. https://doi.org/10.1016/j.enpol.2010.02.059
14. Zhu C, Liu K, Yu C, Ma R, Cheng H (2008) Simulation and experimental analysis on wireless energy transfer on magnetic resonances. IEEE Vehicle Power and Propulsion Conference, Harbin, pp 3–5
15. Tesla N (1914) Apparatus for transmitting electrical energy. United States patent office, US patent no. 1119732, USA
16. Mahmood A, Ismail A, Zaman Z, Fakhar H, Najam Z, Hasan MS, Ahmed SH (2014) A comparative study of wireless power transmission techniques. J Basic Appl Sci Res 4(1):321–326
17. Liu X, Zhang F, Hackworth SA, Sclabassi RJ, Sun M (2009) Modeling and Simulation of a Thin Film Power Transfer Cell for Medical Devices and Implants. IEEE International Symposium on Circuits and Systems (ISCAS), Taipei, pp 3086–3089. https://doi.org/10.1109/ISCAS.2009.5118455
18. Fernandez J.M, Borras J. A (2001) Contactless battery charger with wireless control link. US Patent No. 6184651, USA
19. Scheible G, Smailus B, Klaus M, Garrels K, Heinemann L (2003) System for wirelessly supplying a large number of actuators of a machine with electrical power. US Patent No. 6597076, USA
20. Moffatt RA (2009) Wireless transfer of electric power. Massachusetts Institute of Technology
21. Diekhans T, Doncker RW (2014) A dual-side controlled inductive power transfer system optimized for large coupling factor variations. ECCE 2014:652–659
22. Nagatsuka Y, Ehara N, Kaneko Y, Abe S, Yasuda T (2010) Compact contactless power transfer system for electric vehicle. IPEC2010:807–813
23. Shijo T, Ogawa K, Obayashi S (2015) Optimization of thickness and shape of core block in resonator for 7 kW-class wireless power transfer system for PHEV/EV charging. ECCE2015, pp 3099–3102
24. Kudo T, Toi T, Kaneko Y, Abe S (2014) Contactless power transfer system suitable for low voltage and large current charging for EDLCs. IPEC-Hiroshima, pp 1109–1114
25. Chigira M, Nagatsuka Y, Kaneko Y, Abe S, Yasuda T, Suzuki A (2011) Small-size light-weight transformer with new core structure for contactless electric vehicle power transfer system. ECCE2011, pp 260–266