Systematic Literature Review On Wireless Power Transmission To Multiple Device

Suraj Kumar Panigrahi[1]*, Renu Sharma[2], Durga Prasanna Kar[3], Satyanarayan Bhuyan[4]

***Corresponding Author: -** Suraj Kumar Panigrahi
*1 Dept.of Electrical Engineering, ITER,SOA Deemed to be University Bhubaneswar, INDIA
E-mail:- gm.surajkumar@gmail.com
2 Dept.of Electrical Engineering, ITER,SOA Deemed to be University Bhubaneswar, INDIA, E-mail:- renusharma@soa.ac.in
3 Dept.of Elecronics and Communication Engineering, ITER,SOA Deemed to be University Bhubaneswar, INDIA,
E-mail:- durgakar@soa.ac.in
4 Dept.of Elecronics and Communication Engineering, ITER,SOA Deemed to be University Bhubaneswar, INDIA,
E-mail:- satyanarayanbhuyan@soa.ac.in

Abstract:-

In the recent era we are focusing more and more to develop contactless power transfer technology as plug-in cables have numerous drawbacks like exposed wires, environmental impacts etc. The wireless power transmission system (WPTS) is popular to operate various devices like TV, laptops, cell phones conveniently. Again major challenge is to handle more than one device from a single transmitter. It is found that for a fixed design number of receiver load and load power is fixed. In this letter ancient WPT technology, "Radiative and non-radiative" WPT techniques, theory behind driving multiple receiver, difficulties and future scope of WPT to multiple receiver are discussed.

Index terms: -Wireless power transfer (WPT) to multiple receiver, Magnetic coupling, Resonant Inductive Coupling,

DOI Number: 10.14704/nq.2022.20.9.NQ44356 **Neuro Quantology 2022; 20(9):3082-3091**

INTRODUCTION

Wireless power transfer (WPT) is transmission of electric power from the electrical source to electrical load without a connecting wire. WPT can be used for various application such as to energize bio-medical implants, laptops, cell phones, electric vehicles other household electronic devices [1][2]. Recently researchers are interested to drive multiple device through a single transmitting source coil significantly.

WPT is categorized into radiative and non-radiative according to power transfer mechanism [3]. Transmission can be to a short range smaller than coil diameter. For a mid-range receiver coil placed at a distance 1to 10 times of the coil diameter [4]. For non-radiative power transfer, inductive coupling and capacitive coupling technique is used to achieve near field power transmission. Microwaves or laser beam are used for radiative technique for far field application.
It is found that bi-directional power transfer is providing significant power transfer efficiency over unidirectional power transform [5]. Hence increasing the number of receiver can lead to higher efficiency.

FOUNDATION of WPT SYSTEM

In the year 1820, movement of pointer of a compass observed by Han Oerested when electric current passes through a wire indicating electromagnetic field. Andrie-Marie Ampere derived the relationship between magnetic field and electric field by current law in 1826. Law of electromagnetic induction was established by Faraday in 1831. E field is produce in a conductor along with an air gap, which is proposed by Maxwell After some years. Existence of electromagnetic radiation is proved by Heinrich Hertz in 1888 [6].
Nicola Tesla developed tesla coils for power transmission wirelessly and patented it in the year 1891[7]. In 1894 they operate a lamp using a couple of coil by WPT method.

TECHNIQUES AND SYSTEM DESCRIPTION

WPT can be fall into two techniques, i. far-field (radiative), ii.near field (commonly known as non-radiative).

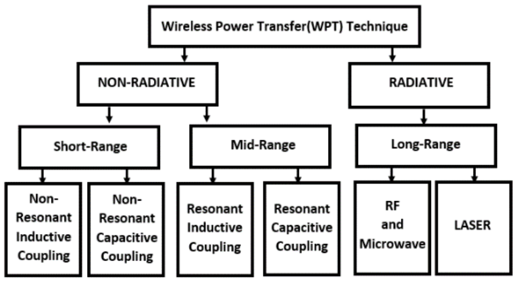

Fig. 1. Flow diagram of different WPT techniques

Radiative Technique

Radiative technique, which is also known as power beaming technique uses electromagnetic radiation (laser beam or microwave). It can transfer power to a long distance providing, its aim must be the receiver. So technically it is directional. [8] a study has suggested a micro wave transmission with a frequency of 2.45GHz to be utilized to solar power satellite. Now a days directive method is used to charge EVs remotely [9].

Non-Radiative Technique

Non radiative power transfer technique or near field technique again falls into short range WPT and mid-range WPT.

Capacitive and Inductive coupling techniques are used for short range wireless power transfer, usually less than the coil diameter.

Capacitive Coupling Method

Over an electric field using two electrodes the power transfer takes place in capacitive coupling WPT technique. The transferred power quantity is proportional to the frequency range. This is useful for low power application where energy transfer through metal plates, such as to charge biomedical implants. For high power implants it cannot be useful as it harms the human. Capacitive coupling can be further classified in to i. Unipolar or longitudinal design ii. Bipolar design. For bipolar design, receiving plates are continuously adjusted according to the charging plates.

Inductive Coupling Method

Inductive coupling is very popular for its simple working principle. In this technique primary coil is excited by a time varying current resulting a varying magnetic flux. This cuts by the secondary coil, which produce an EMF voltage at the coil as a result. It works like air-core transformer by faraday's law of electro-magnetic induction.

Dr. Jagdish C. Bose, ring a bell remotely using electromagnetic waves in [10].A 75W motor of an airship, at a distance of around 100 feet was driven by WPT method [11].

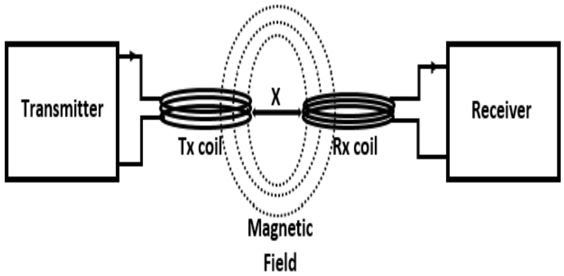

Fig. 2. Inductive Coupled Wireless Power Transfer System

The above figure.2 shows a general inductive coupled WPT system. Magnetic field is created in the transmitter coil (Tx) due to time varying current from transmitter side. Receiver coil (Rx) get induced to the magnetic field and an EMF is generated in the Rx coil, thoroughly transfer to the receiver unit.

Magnetic field from the transmitter can be increased by increasing current, number of turns or Tx radious. However, it has certain limits as it is dependent on frequency. Counting Self-resonance frequency, skin effect, proximity effects one cannot arbitrarily change the size of the coils (no.of turns) [12].

Again the placement of the receiver with respect to transmitter is very vital for maximum efficiency. The receiver coil must be placed in such a way that it cuts maximum number of magnetic lines of force coming from the transmitting coil [13].

A group of researcher from MIT, using a couple of coil which they call 'Witricity' energized a 60W bulb placed at a distance of 2m with antenna diameter 60 cm. Introducing magneto resonant the system efficiency can be increased [14].

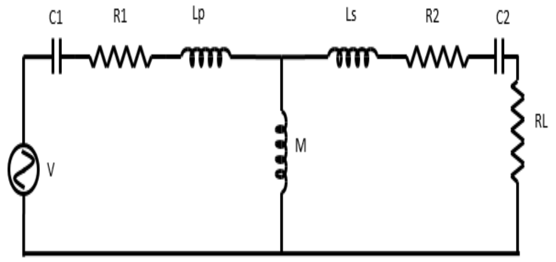

Fig. 3. Circuit Diagram of Resonant Inductive Couple Circuit

Resonant Inductive Coupling Technique

The above figure shows a resonant inductive couple circuit. It can be done connecting competition capacitor to the coil to eliminate the inductance effect so the circuit will act as purely resistive circuit enhancing the current flow. For transmitter side both the component can be connected in series and parallel same in the receiver side. So 4 possible topologies are series series(SS), series Parallel (SP), parallel series (PS), parallel parallel (PP). It is found that SS and SP are suitable for EV charging [15].

It is found that resonant inductive couple WPT system has more advantages than the inductive coupling WPT system. Resonant inductive systems are prone to other metal interference, efficient, works as open circuit when the receiver is not placed (like a plug-in charger), power will transfer to the resonating receiver coil only. These makes the resonant inductive coupled WPT system robust [16]. Rim and colleague transmitted inductive power to a distance of 3,4 and 5m with an efficiency of 29%, 16%, and 8% respectively with a frequency of 20 kHz at "KAIST" University in 2014 [17]. Commercial devices like hair trimer, toys, electronic toothbrush are adopted fixed position receiver load[18]. Inductive coils generate eddy current in the conductor which may lead to shock, flickering and arcing hazards. In [19-22] developed a high frequency WPT system using a class E, for a transmitting efficiency of 75.7% with a frequency 134kHz, 295W power. For a medical application 20W transferred to a distance of 1cm with a efficiency of 80% [23]. "MagMIMO" is developed by MIT research group to charge a device at a distance of around 30cm away [24].

Magnetic resonance based Bi-directional WPT

The electromagnetic lines of force are scattered around the transmitting coil. The unidirectional system or single receiver system avail only a part of the total magnetic lines of force created by the transmitter. Dr. D. P. Kar and team has experimentally shows, adoption of bi-directional power transfer method, can powered up or charge two electronic device simultaneously without affecting the optimum power transfer efficiency [25].The power transfer efficiency increased to 88% by using this technique [25].

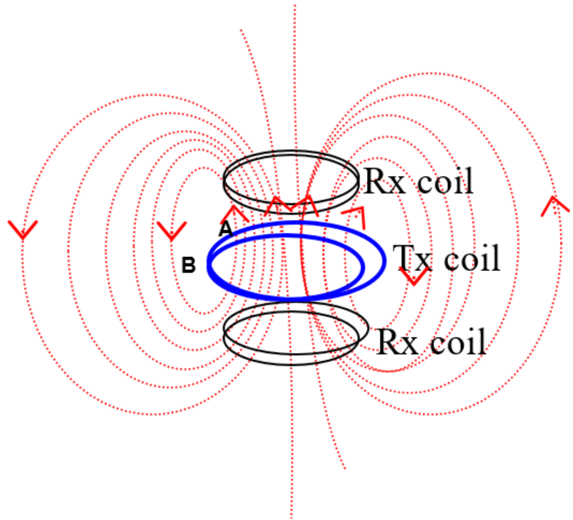

Fig. 4. Coil positioning of bi-directional inductive coupled WPT

Author experimented two small receiver coil from a large source coil, and found splitting of frequency due to close placement of the both receiver which makes them relatively stronger coupled. To omit the issue a controller circuit is attached which will track the frequency shift and can adjust the capacitance accordingly [26].From the above [25] we can expect increasing the number of receiver coil can enhance the power transfer efficiency.

Magnetic resonance based WPT to multiple receiver

The below Fig.5 shows circuit representation of a resonant inductive couple WPT to multiple receiver. Magnetic resonance inductive coupling enables wireless power transfer, from one transmitter to multiple receiver simultaneously.

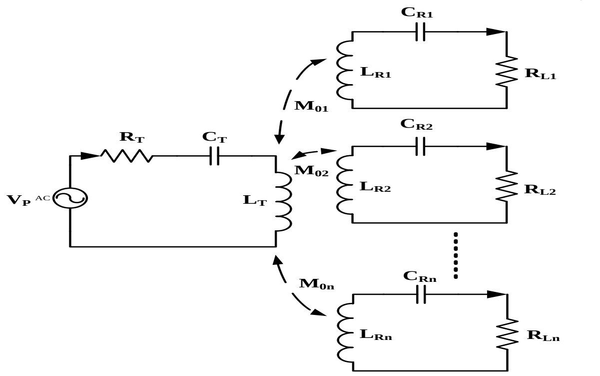

Fig. 5. Resonant inductive coupled WPT to multiple receiver

The overall system efficiency depends on the loads and receiver position, in a multiple receiver system. Author analyze optimal load and power distribution and found under optimal load condition more than 80% efficiency can be achieved with three different receivers at a 13.56 MHz frequency [27].Taking M number of transmitter coil and N number of receiver coil, has advantages over single transmitter coil. Parallel connection of transmitter reduce the inductance makes the system less sensitive to variation of the component. Again the power deliver to each receiver is less sensitive to the loads attached to the other coils. Taking 1:2 coupling to 2:2 coupling, changing a small amount of coupling efficiency they received power increase from 1.8W to 9.5W [28]. It allows simultaneous charging of multiple electronics devices.

In a mid-range WPT when the receiver is at several times than the size of the resonator, the effect of adding multiple receivers is explained in the manuscript. Experimentally shown that even if the efficiency of each receiver is low, the overall efficiency is high [29].In between the transmitter and receivers keeping a intermediate resonant coil properly can improve the efficiency significantly [30]. The intermediate coil must be placed perpendicularly as well as coaxially to both Tx and Rx coil.A load coil is introduced in addition to the system, enhancing the structure and power flow control. Both single load multi load power transfer has analyzed and found to be good to employ load coils[31] [32].

A general analysis on multiple receiver power transfer system, cross coupling effect in accordance to it how to eliminate cross coupling effect among the receiver has shown in [33]. Analytically optimal loads are derived as well as verified. A novel transmitter, configure in cubic structure can generate homogeneous genuine 3D high degree of freedom magnetic field allowing eight pick-ups. This design enables 30 W total power transfer which can meet all low power device [34].

A single input and multiple output (SIMO) WPT was investigated by deriving optimal load to maximize total efficiency and then analytical formula for desired power distribution ratio. Power distribution among the loads in SIMO WPT is demonstrated [35]. In 2020 author proposed two methods, equal power distribution and sequential power distribution. Experimented and found these methods are slower the charging process over conventional charging method [36].In 2020 a web form scheduling algorithm has difficulties is to solve the non-convex optimization problem. To overcome this low complexity approximated algorithm is developed which enhance the performance [37].

Article presented a WPT system with multiple frequency and multiple receivers. With the proposed structure six kind of concurrent double frequency and a single ternary frequency can be possible without changing the transmitter circuit minimizing volume and cost [38]. Resonant inductive coupling wireless power transfer often suffers from output power fluctuation due to interference of the receiver coils and resonant frequency tolerance. Keeping a control to fixed transmitter current amplitude and keeping each receiver current phase orthogonal to transmitter current, the above problems can be overcome [39].

The problem in multiple receiver system is to determine optimal or ideal load for maximization of efficiency. It can be found out applying maximum power transfer theorem for N ports [40]. In multiple transmitter as well as receiver in a limited space, within the transmitters and receivers coupling occurs. Due to such coupling, effective resonant frequency is changed.

Therefore, author proposed frequency condition for maximum efficiency & power transfer for such coupling [41].The required amount and type of adjustment are provided accordingly. Experiment has been done to prove the above frequency adjustment. Even in a low coupling like 0.025-0.063 getting a efficiency from 45%-57% using the technique.

Selective flow of power to load is an important issue among multiple receiver WPT system. A new method to control power division has proposed. RWPT in a two coil system has been analyzed introducing four important factors. Efficiency at its maximum when the driving frequency equals to the resonant frequency of receiver coil. Using the technique power can be transferred to different load of different resonant frequency [42].This presented a technique for impedance matching for WPT to multiple receiver considering cross coupling effects between non-adjacent coils. A single transmitter with three receiver WPT system has fabricated, without a compensation capacitance or other impedance matching circuit. Simulated results show by using this method more than 85% efficiency can be achieved regardless of number of receiver unlike conventional method [43].

In a multi receiver WPT system, most power transferred to the receiver closest to the transmitter. Impedance matching method is investigated in the letter, providing high overall transfer efficiency with adjustable power distribution among the receiver [44].Using couple mode theory, the system efficiency was calculated and a dual load series resonant WPT system was investigated. Interference of aluminum material is analyzed through JMAG. Principle of eddy current loss adopted to get transmission characteristics, WPT platform was established with the resonant frequency of 96 kHz [45].

In WPT system optimization means impedance matching and tracking of split frequency. In a multiple transmitter system, optimization of transmitting signal can significantly improve the efficiency. To prove the above an iterative algorithm for optimization of transmitting signal for three orthogonal transmitter and multiple single coil receiver system proposed [46].To minimize cross interference caused by multi frequency in WPT system, auxiliary circuits as a band pass (BP) or band stop (BS) circuits and optional relay circuits are employed for enhancement of power transfer and load selection. This technique enables the non-targeted receiver to act as a resonator to enhance magnetic coupling, and operating frequency need not to be widely apart as BP and BS circuits are employed [47].

A selective unidirectional WPT to multiple receiver technique is proposed. Three orthogonal coils combined for the transmitter, transfer power to any nearby receiver. As number of transmitter reduced cost and space also minimized. Band pass filter principle selects the receiver and enhances the power transfer efficiency. Both simulation and experiment has led to prove the above [48]. In this letter a single transmitter can charge both strongly couple receiver as well as weakly coupled receiver. In the proposed experiment 30W receiver can operate range from 1.9-7.5 cm [49].

Under multi transmitter, there is a upper bound for WPT. Simulation demonstrated by using efficient electrically small folded cylindrical helix dipole boundary can be handled. Experiment shows 17% power transfer efficiency value over 0.3$\boldsymbol{\lambda}$ region between two transmitters [50].It discus the effect of load and mutual inductance on the system efficiency. Optimal loads, input impedance, and power distribution are analyzed. From the proposed experiment, under optimal load condition above 80% efficiency can be achieved for a system with three different receivers working at 13.56MHz [51].

In the letter WPT to multiple receiver was investigated on the basis of system efficiency, mutual inductance, load and optimal load, reflected impedance, power division method were analyzed and a control scheme proposed. P&O algorithm used as the control scheme for charging current control, and found to be 80% efficient with a fixed power division ratio system working at 6.78MHz [52]. In this paper a passive N-port network designed and optimized resistive as well as reactive component of loads, with derived expression. The closed form expression of optimal loads can achieve maximum efficiency irrespective to any coupling conditions via any media [53].

In multiple WPT system, simultaneous PT is important as well as overall efficiency. External loads can harm coupling efficiency, hencea two receiver system is modeled and analyze the optimal external loads with maximize coupling efficiency at a driven frequency of 13.56MHz [54].In multiple WPT system, equal power distribution maintaining high efficiency is very challenging. In this paper a smart selective WPT technique is introduced. Eliminating cross coupling effect, it delivers power to one device. Experimented and shown for a very small coupling of 0.01 using the technique, efficiency becomes 24% - 29% also power distribution was demonstrated [55].An optimization problem is designed for far field WPT, converting it from non-convex to a convex problem with proper approximation and generated RF wave for transmitting to far field. This overcomes the problem like power attenuation of RF signal due to distance [56].

In this article an intermediate coil is placed to supply same power to the multiple receiver load over various distance. The intermediate coil works as relay resonator as well as a power receiver. Source matching, load matching, transfer quality and reflected impedance these four factors are used to derive mathematical model for n-load system. Experimentally investigated and for double load and three load system are proved [57].Taking a more abstract approach, altering WPT system to a linear system expressing input output using less number of unknown parameter. Simple derivations are formulated for maximize transfer efficiency as well as optimal excitations. A method circuit sounding is used for estimating unknown parameter and four transmitting to two receiving coil system has examined [58].A WPT system has been designed with class E power amplifier at a frequency band of 6.78MHz. the proposed system used for nine charging cases in three types of Rx coils and got efficiency from 70.7-85.5% and power from 8.6-45.7W at a receiving distance of 30cm [59].

A 6.78MHz WPT to multiple receiver system using a class E power amplifier developed. Constant 5V, 9V, and 12V output voltage can be achieved independently for different receiver with overall efficiency of 66.6% [60].In WPT field coupling can be enhance by introducing metasurfaces. Multiple receivers can be fed and robust operation against load or position variation can be achieved using Metasurface based WPT system. A particular example of N identical receiver is discussed [61].Applying maximum power transfer theorem for an N-port, optimal load for max power transfer in a WPT system is formulated. Simple expression for load impedance been derived and equivalent circuit has simulated [62].

A single transmitter to multiple receiver WPT system circuit modeled and optimal load, peak power efficiency calculated analyzed. An experimental circuit simulated and calculated the efficiency with the proposed scheme [63]. In a multiple WPT system irrelevant circuit topology causes disturbance among receivers due to inductive cross coupling. To overcome the problem a K-inverter is employed at 0 ***Ω*** output impedance in order to isolate the receiver from each other in accordance to this power distribution to each load is independent of other load. Load isolation principle is illustrated in detailed experimentally with three receiver WPT system and verified the theory [64].Here a multi-frequency multi-power (MFMP) WPT system has implemented from single transmitter to multiple receiver. Implementing this type of WPT system compromise system complexity, difficulty in control, switching frequency, transmission efficiency. Only using artful inverter topology, the proposed MFMP-WPT system can effectively overcome the problem [65].

Load independent output in a multiple receiver WPT system still lagging in research. This letter investigated characteristics of voltage output in multiple WPT with changing load and find out operating frequency for a constant output voltage. When coupling coefficient is low, two frequencies can achieve load independent voltage output and when coupling is high only one frequency can gives output voltage independent to load [66].How deliver power to each receiver is affected due to shift in resonant frequency in a multiple receiver WPT system. A mathematical frame work developed and experimentally demonstrated that if each receiver tuned to the frequency emitted by transmitter we can overcome the problem [67].

Power division ratio (PDR) in WPT from a one to one system than one to many receiver is addressed by using equivalent circuit. The PDR of each receiver inversely proportional to load resistance. A transmitter and intermediate couplers arranged on equal distance, need to switch control strategy to adjust load resistance according to parity number on WPT multiple receiver [68].

A network approach is used in a multiple transmitter to multiple receiver IPT for a link, aims to maximize the delivered power to the receiver has been solved analytically and validated by circuital simulations [69].A battery cell voltage equalization approach using multiple receiver WPT working at MHz. using a class E power amplifier system has been experimented and found that using the above technique efficiency above 70% can be achieved when six Li battery under loosely coupled (k=0.065) [70].Repeater coils are introduced for multiple loads. Two repeater coil in a repeater unit, one is to receive power from preceding unit and other to transmit power to subsequent unit. Series –parallel-series compensation is adopted for repeater unit, in order to get independent power control of all the loads. Neglecting parasitic resistance of coil fixed current can be obtain for the load with proper resonant condition. The above is validated by effectively experimented [71].Autonomous underwater vehicle (AUV) cluster system is empowered by a multi-load WPT system. To get concentrated magnetic field, solenoid transmitter coil is designed. To form stronger magnetic field, the adjacent transmitter coils are reversely wound which enhance the coupling. A LCC-LCC compensation multi-load WPT prototype established experimented and verified system efficiency to be 90% and each receiver can get 500W under different angle between any two receivers [72].

FUTURE CHALLENGES

In a multiple receiver configuration operation optimization is dire challenge. Design and development of practical control scheme for optimize power distribution [33]. It is still a misconception that one transmitter coil can drive as many as receiver load coils in a multiple resonant inductive power transfer system. For a fixed coil design number of receiver load and load power is fixed. The relation between individual mutual inductance and the equivalent mutual inductance of a multiple receiver coil system is not established yet. How the receiver coils must place for optimal power transfer? We are working on these findings currently.

CONCLUSION

Resonant inductive wireless power transfer technology to multiple devices drawing more attention for its advantages in industrial and electronic applications. The systematic literature review, design history, ancient WPT method, today’s scenario and future challenges were discussed.

REFERENCES

Ma, Dharani, and Ravi Kb. "Systematic literature review on wireless power transmission." *Turkish Journal of Computer and Mathematics Education Vol* 12, no. 10 (2021): 4400-4406.

Tan, Yen Kheng. *Energy harvesting autonomous sensor systems: design, analysis, and practical implementation*. CRC Press, 2013.

Hui, Shu Yuen Ron, Wenxing Zhong, and Chi Kwan Lee. "A critical review of recent progress in mid-range wireless power transfer." *IEEE Transactions on Power Electronics* 29, no. 9 (2013): 4500-4511.

Gowda, Vinay R., Okan Yurduseven, Guy Lipworth, Tomislav Zupan, Matthew S. Reynolds, and David R. Smith. "Wireless power transfer in the radiative near field." *IEEE Antennas and Wireless Propagation Letters* 15 (2016): 1865-1868.

Kar, Durga P., Praveen P. Nayak, Satyanarayan Bhuyan, and Debasish Mishra. "Bi-directional magnetic resonance based wireless power transfer for electronic devices." *Applied Physics Letters* 107, no. 13 (2015): 133901.

Ma, Dharani, and Ravi Kb. "Systematic literature review on wireless power transmission." *Turkish Journal of Computer and Mathematics Education Vol* 12, no. 10 (2021): 4400-4406.

Marincic, A. S. "Nikola tesla and the wireless transmission of energy." *IEEE Transactions on Power Apparatus and Systems* 10 (1982): 4064-4068.

Landis, Geoffrey A. "Re-evaluating satellite solar power systems for earth." In *2006 IEEE 4th World Conference* *on Photovoltaic Energy Conference*, vol. 2, pp. 1939-1942. IEEE, 2006.

Shinohara, Naoki. "Beam efficiency of wireless power transmission via radio waves from short range to long range." *Journal of electromagnetic engineering and science* 10, no. 4 (2010): 224-230.

Emerson, Darrel T. "The work of Jagadis Chandra Bose: 100 years of millimeter-wave research." *IEEE transactions on microwave theory and techniques* 45, no. 12 (1997): 2267-2273.

Sun, Tianjia, Xiang Xie, and Zhihua Wang. *Wireless power transfer for medical microsystems*. New York: Springer, 2013.

Mayordomo, Iker, Tobias Dräger, Peter Spies, Josef Bernhard, and Alexander Pflaum. "An overview of technical challenges and advances of inductive wireless power transmission." *Proceedings of the IEEE* 101, no. 6 (2013): 1302-1311.

Sahany, Siddharth, Sushree Sangita Biswal, Durga Prasanna Kar, Asru Abhijit Pattnaik, and Satyanarayan Bhuyan. "Receiver coil position selection through magnetic field coupling of a WPT system used for powering multiple electronic devices." *Progress In Electromagnetics Research M* 85 (2019): 165-173.

Kurs, Andre, Aristeidis Karalis, Robert Moffatt, John D. Joannopoulos, Peter Fisher, and Marin Soljačić. "Wireless power transfer via strongly coupled magnetic resonances." *science* 317, no. 5834 (2007): 83-86.

Cui, S., Z. Z. Liu, Y. J. Hou, H. Zeng, Z. K. Yue, and L. H. Liang. "Study on efficiency of different topologies of magnetic coupled resonant wireless charging system." In *IOP Conference Series: Earth and Environmental Science*, vol. 93, no. 1, p. 012064. IOP Publishing, 2017.

Kar, Durga Prasanna, Praveen Priyaranjan Nayak, Satyanarayan Bhuyan, and Sanjib Kumar Panda. "Study of resonance-based wireless electric vehicle charging system in close proximity to metallic objects." *Progress In Electromagnetics Research M* 37 (2014): 183-189.

Park, Changbyung, Sungwoo Lee, Gyu-Hyeong Cho, and Chun T. Rim. "Innovative 5-m-off-distance inductive power transfer systems with optimally shaped dipole coils." *IEEE transactions on power electronics* 30, no. 2 (2014): 817-827.

Hui, S. Y. "Planar wireless charging technology for portable electronic products and Qi." *Proceedings of the IEEE* 101, no. 6 (2013): 1290-1301.

Hui, R. S. Y., & Tang, S. C. (2005). U.S. Patent No. 6,888,438. Washington, DC: U.S. Patent and Trademark Office.

Liu, X., and S. Y. R. Hui. "An analysis of a double-layer electromagnetic shield for a universal contactless battery charging platform." In *2005 IEEE 36th Power Electronics Specialists Conference*, pp. 1767-1772. IEEE, 2005.

Low, Zhen Ning, Raul Andres Chinga, Ryan Tseng, and Jenshan Lin. "Design and test of a high-power high-efficiency loosely coupled planar wireless power transfer system." *IEEE transactions on industrial electronics* 56, no. 5 (2008): 1801-1812.

Low, Zhen Ning. *High efficiency loosely coupled wireless power transfer system via magnetic induction*. University of Florida, 2009.

Vandevoorde, Glenn, and Robert Puers. "Wireless energy transfer for stand-alone systems: a comparison between low and high power applicability." *Sensors and Actuators A: Physical* 92, no. 1-3 (2001): 305-311.

Jadidian, Jouya, and Dina Katabi. "Magnetic MIMO: How to charge your phone in your pocket." In *Proceedings of the 20th annual international conference on Mobile computing and networking*, pp. 495-506. 2014.

Kar, Durga P., Praveen P. Nayak, Satyanarayan Bhuyan, and Debasish Mishra. "Bi-directional magnetic resonance based wireless power transfer for electronic devices." *Applied Physics Letters* 107, no. 13 (2015): 133901.

Cannon, Benjamin L., James F. Hoburg, Daniel D. Stancil, and Seth Copen Goldstein. "Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers." *IEEE transactions on power electronics* 24, no. 7 (2009): 1819-1825.

Fu, Minfan, Tong Zhang, Chengbin Ma, and Xinen Zhu. "Efficiency and optimal loads analysis for multiple-receiver wireless power transfer systems." *IEEE Transactions on Microwave Theory and Techniques* 63, no. 3 (2015): 801-812.

Casanova, Joaquin J., Zhen Ning Low, and Jenshan Lin. "A loosely coupled planar wireless power system for multiple receivers." *IEEE Transactions on Industrial Electronics* 56, no. 8 (2009): 3060-3068.

Kurs, Andre, Robert Moffatt, and Marin Soljačić. "Simultaneous mid-range power transfer to multiple devices." *Applied Physics Letters* 96, no. 4 (2010): 044102.

Kim, JinWook, Hyeon-Chang Son, Kwan-Ho Kim, and Young-Jin Park. "Efficiency analysis of magnetic resonance wireless power transfer with intermediate resonant coil." *IEEE Antennas and Wireless Propagation Letters* 10 (2011): 389-392.

Zhang, Yiming, Ting Lu, Zhengming Zhao, Fanbo He, Kainan Chen, and Liqiang Yuan. "Employing load coils for multiple loads of resonant wireless power transfer." *IEEE Transactions on power electronics* 30, no. 11 (2015): 6174-6181.

PAVANI, D., M. VARASUNDAR, and K. RAMBABU. "Employing Load Coils for Multiple Loads of Resonant Wireless Power Transfer." (2016).

Fu, Minfan, Tong Zhang, Xinen Zhu, Patrick Chi-Kwong Luk, and Chengbin Ma. "Compensation of cross coupling in multiple-receiver wireless power transfer systems." *IEEE Transactions on Industrial Informatics* 12, no. 2 (2016): 474-482.

Rong, Cancan, Xiangrui He, Minghai Liu, Yuying Wang, Xiaobo Liu, Conghui Lu, Yingqin Zeng, and Renzhe Liu. "Omnidirectional Free-degree Wireless Power Transfer System Based on Magnetic Dipole Coils for Multiple Receivers." *IEEE Access* (2021).

Kim, Gunyoung, Seunghyun Boo, Sanghoek Kim, and Bomson Lee. "Control of power distribution for multiple receivers in SIMO wireless power transfer system." *Journal of electromagnetic engineering and science* 18, no. 4 (2018): 221-230.

Lee, Kisong, and Hyun-Ho Choi. "Fast wireless power transfer for multiple receivers in linear topology." *IEEE Systems Journal* 14, no. 1 (2019): 649-652.

Kim, Kyeong-Won, Hyun-Suk Lee, and Jang-Won Lee. "Opportunistic waveform scheduling for wireless power transfer with multiple devices." *IEEE*

Transactions on Wireless Communications 19, no. 9 (2020): 5651-5665.

Xiao, Yang, Chunhua Liu, Yongcan Huang, and Senyi Liu. "Concurrent wireless power transfer to multiple receivers with additional resonant frequencies and reduced power switches." *IEEE Transactions on Industrial Electronics* 67, no. 11 (2019): 9292-9301.

Ishihara, Masataka, Keita Fujiki, Kazuhiro Umetani, and Eiiji Hiraki. "Autonomous System Concept of Multiple-Receiver Inductive Coupling Wireless Power Transfer for Output Power Stabilization Against Cross-Interference Among Receivers and Resonance Frequency Tolerance." *IEEE Transactions on Industry Applications* (2021).

de Souza, Wanberton Gabriel, Luciano Coutinho Gomes, Lucas Rocha Lannes, and Darizon Alves Andrade. "Analysis and Modeling of a Wireless Power Transmission System for Multiple Receivers." *IEEE Latin America Transactions* 19, no. 12 (2021): 1987-1994.

Ahn, Dukju, and Songcheol Hong. "Effect of coupling between multiple transmitters or multiple receivers on wireless power transfer." *IEEE Transactions on Industrial Electronics* 60, no. 7 (2012): 2602-2613

Zhang, Yiming, Ting Lu, Zhengming Zhao, Fanbo He, Kainan Chen, and Liqiang Yuan. "Selective wireless power transfer to multiple loads using receivers of different resonant frequencies." *IEEE Transactions on Power Electronics* 30, no. 11 (2014): 6001-6005.

Kim, J., H-C. Son, D-H. Kim, and Y-J. Park. "Impedance matching considering cross coupling for wireless power transfer to multiple receivers." In *2013 IEEE Wireless Power Transfer (WPT)*, pp. 226-229. IEEE, 2013.

Lee, Kisong, and Dong-Ho Cho. "Analysis of wireless power transfer for adjustable power distribution among multiple receivers." *IEEE Antennas and Wireless Propagation Letters* 14 (2015): 950-953.

Huang, Xiaoyan, Yuqing Gao, Jing Zhou, Jien Ma, Jian Zhang, and Youtong Fang. "Magnetic field design for optimal wireless power transfer to multiple receivers." *IET Power Electronics* 9, no. 9 (2016): 1885-1893.

Kisseleff, Steven, Ian F. Akyildiz, and W. Gerstacker. "Beamforming for magnetic induction based wireless power transfer systems with multiple receivers." In *2015 IEEE Global Communications Conference (GLOBECOM)*, pp. 1-7. IEEE, 2015.

Zhong, Wenxing, and S. Y. R. Hui. "Auxiliary circuits for power flow control in multifrequency wireless power transfer systems with multiple receivers." *IEEE Transactions on Power Electronics* 30, no. 10 (2014): 5902-5910.

Dai, Zhongyu, Zhijian Fang, Hong Huang, Yuanjian He, and Junhua Wang. "Selective omnidirectional magnetic resonant coupling wireless power transfer with multiple-receiver system." *IEEE Access* 6 (2018): 19287-19294.

Ahn, Dukju, Seong-Min Kim, Sang-Won Kim, Jung-Ick Moon, and In-Kui Cho. "Wireless power transfer receiver with adjustable coil output voltage for multiple receivers application." *IEEE Transactions on Industrial Electronics* 66, no. 5 (2018): 4003-4012.

Yoon, Ick-Jae, and Hao Ling. "Investigation of near-field wireless power transfer under multiple transmitters." *IEEE Antennas and Wireless Propagation Letters* 10 (2011): 662-665.

Fu, Minfan, Tong Zhang, Chengbin Ma, and Xinen Zhu. "Efficiency and optimal loads analysis for multiple-receiver wireless power transfer systems." *IEEE Transactions on Microwave Theory and Techniques* 63, no. 3 (2015): 801-812.

Li, Yang, Kai Song, Zhenjie Li, Jinhai Jiang, and Chunbo Zhu. "Optimal efficiency tracking control scheme based on power stabilization for a wireless power transfer system with multiple receivers." *Energies* 11, no. 5 (2018): 1232.

Duong, Quang-Thang, and Minoru Okada. "Maximum efficiency formulation for inductive power transfer with multiple receivers." *IEICE Electronics Express* 13, no. 22 (2016): 20160915-20160915.

Zhang, Tong, Minfan Fu, Chengbin Ma, and Xinen Zhu. "Optimal load analysis for a two-receiver wireless power transfer system." In *2014 IEEE Wireless Power Transfer Conference*, pp. 84-87. IEEE, 2014.

Kim, Young-Joon, Dohyuk Ha, William J. Chappell, and Pedro P. Irazoqui. "Selective wireless power transfer for smart power distribution in a miniature-sized multiple-receiver system." *IEEE Transactions on Industrial Electronics* 63, no. 3 (2015): 1853-1862.

Kim, Kyeong-Won, Hyun-Suk Lee, and Jang-Won Lee. "Waveform design for fair wireless power transfer with multiple energy harvesting devices." *IEEE Journal on Selected Areas in Communications* 37, no. 1 (2018): 34-47.

Zhang, Yiming, Ting Lu, Zhengming Zhao, Kainan Chen, Fanbo He, and Liqiang Yuan. "Wireless power transfer to multiple loads over various distances using relay resonators." *IEEE Microwave and Wireless Components Letters* 25, no. 5 (2015): 337-339.

Arakawa, Tomohiro, Sairam Goguri, James V. Krogmeier, Anton Kruger, David J. Love, Raghuraman Mudumbai, and Matthew A. Swabey. "Optimizing wireless power transfer from multiple transmit coils." *IEEE Access* 6 (2018): 23828-23838.

Oh, Hansik, Sungjae Oh, Hyungmo Koo, Woojin Choi, Jaekyung Shin, Keum Cheol Hwang, Kang-Yoon Lee, and Youngoo Yang. "Mid-range wireless power transfer system for various types of multiple receivers using power customized resonator." *IEEE Access* 9 (2021): 45230-45241.

Fu, Minfan, He Yin, Ming Liu, Yong Wang, and Chengbin Ma. "A 6.78 MHz multiple-receiver wireless power transfer system with constant output voltage and optimum efficiency." *IEEE Transactions on Power Electronics* 33, no. 6 (2017): 5330-5340.

Liu, Fei, Prasad Jayathurathnage, and Sergei A. Tretyakov. "Active metasurfaces as a platform for capacitivewireless power transfer supporting multiple receivers." In *2019 Thirteenth International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials)*, pp. X-227. IEEE, 2019.

Monti, Giuseppina, Marco Dionigi, Mauro Mongiardo, and Renzo Perfetti. "Optimal design of wireless energy transfer to multiple receivers: Power maximization." *IEEE Transactions on Microwave Theory and Techniques* 65, no. 1 (2016): 260-269.

Liu, Xiaochang, Gaofeng Wang, and Wen Ding. "Efficient circuit modelling of wireless power transfer to multiple devices." *IET Power Electronics* 7, no. 12 (2014): 3017-3022.

Kuang, Jiwei, Bin Luo, Yanling Zhang, Yao Hu, and Yiqiang Wu. "Load-isolation wireless power transfer with K-inverter for multiple-receiver applications." *IEEE Access* 6 (2018): 31996-32004.

Liu, Wei, K. T. Chau, Christopher HT Lee, Chaoqiang Jiang, Wei Han, and W. H. Lam. "Multi-frequency multi-power one-to-many wireless power transfer system." *IEEE Transactions on Magnetics* 55, no. 7 (2019): 1-9.

Sun, Longzhao, Houjun Tang, and Shuai Zhong. "Load-independent output voltage analysis of multiple-receiver wireless power transfer system." *IEEE Antennas and Wireless Propagation Letters* 15 (2015): 1238-1241.

Pantic, Zeljko, Kibok Lee, and Srdjan M. Lukic. "Receivers for multifrequency wireless power transfer: Design for minimum interference." *IEEE Journal of Emerging and Selected Topics in Power Electronics* 3, no. 1 (2014): 234-241.

Shimada, Akiro, Yuki Ito, Hideyuki Uehara, and Takashi Ohira. "Effect of hop counts on power division ratio in multi-hop power transfer via magnetic resonance." In *2013 IEEE Wireless Power Transfer (WPT)*, pp. 179-182. IEEE, 2013.

Monti, Giuseppina, Qinghua Wang, Wenquan Che, Alessandra Costanzo, Franco Mastri, and Mauro Mongiardo. "Maximum wireless power transfer for multiple transmitters and receivers." In *2016 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO)*, pp. 1-3. IEEE, 2016.

Liu, Ming, Minfan Fu, Yong Wang, and Chengbin Ma. "Battery cell equalization via megahertz multiple-receiver wireless power transfer." *IEEE Transactions on Power Electronics* 33, no. 5 (2017): 4135-4144.

Cheng, Chenwen, Zhe Zhou, Weiguo Li, Chong Zhu, Zhanfeng Deng, and Chunting Chris Mi. "A multi-load wireless power transfer system with series-parallel-series compensation." *IEEE Transactions on Power Electronics* 34, no. 8 (2019): 7126-7130.

Yan, Zhengchao, Kehan Zhang, Lin Qiao, Yuli Hu, and Baowei Song. "A Multi-Load Wireless Power Transfer System with Concentrated Magnetic Field for AUV Cluster System." *IEEE Transactions on Industry Applications* (2021).

Juliet, Vimala, Sanjeevikumar Padmanaban, and Lucian Mihet-Popa. "Frequency splitting elimination and cross-coupling rejection of wireless power transfer to multiple dynamic receivers." *Applied Sciences* 8, no. 2 (2018): 179.

Bien, Franklin, Woojin Park, Bonyoung Lee, and Gangil Byun. "Metal Surface Guided-Wireless Power Transfer System for Portable Applications with Multiple Receivers." *IEEE Access* (2021).