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Review of Magnetic Coupling Resonance Wireless Energy Transmission

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Abstract

This paper reviews the magnetic coupling resonance wireless energy transmission from the principle, models and theories based on the development and classification of wireless energy transmission technologies. Firstly, it introduces MIT coupled mode theory and the main circuit theory models and experiments, summarizes and illustrates the characteristics of the two theories. Secondly, it introduces the worldwide research progress in this area, including the circuit theories, three-coil energy transfer systems, multi-receptor, four-coil energy transfer systems, frequency tunable resonance body, adaptive tuning and frequency division, the loss distribution, new materials, mutual inductance coupling and frequency tracking. Finally combined with the main research content of magnetically coupled resonant wireless energy transmission, it points out the existing problems and the direction for the studies of the theory and application next step.

Keywords: *wireless energy transmission; magnetic coupling; resonance*

1. Introduction

At the end of the 19th century, Nikola Tesla proposed that applying the capacity of storing charge of the earth, wireless energy transmission can be realized through electric field coupling, and he developed a prototype to test his theory. In the following explorations of wireless energy transmission, a variety of wireless energy transmission methods such as microwave, laser, radio frequency, electromagnetic induction *etc.* have emerged.

In 2006, a research team headed by Marin Soljacic, who is an assistant professor of physics in the Massachusetts Institute of Technology (MIT) proposed a new concept of magnetic coupling resonance wireless energy transmission [1]. Based on the coupled mode theory, they demonstrate the feasibility of the technology called “Witricity” which is able to transfer energy wirelessly. The experimental verification was conducted successfully in 2007. They think that a coupled resonators system which shares the same resonant frequency (such as sound, electromagnetic fields, *etc.*) can realize high-efficiency energy transfer, and the system have little effect on the surrounding environment which has different resonance frequency. In the experiments, they used two self-resonant spiral coil with radius of 30cm and high quality factor (Q = 950) as a resonance to transfer energy. When the operating frequency was around 9.9MHz, they successful lighted up a 60W bulb 2m away. The energy transmission efficiency was about 40% to 60% [1, 2].

According to energy transmission mechanism, the existing wireless energy transmission techniques can mainly be classified into following three types.

The first category is electromagnetic radiation wireless energy transfer, also called the

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technology of far field wireless transmission. The technologies transfer energy by electromagnetic wave like radio frequency signals. The most commonly used technologies are microwave energy transfer (MPT) and laser energy transfer (LPT);

The second category is non-radiated inductively coupled energy transfer (ICPT) which belongs to the near-field wireless transmission technology and based on the law of electromagnetic induction. The technology is based on conventional transformer principles that both sides of the transformer are isolated and the energy transfer by one side of the transformer is coupled to the secondary side through the air gap or other dielectric induction.

The third category is the technology of non-radiation magnetic resonance wireless energy transmission which is also regarded as a near-field wireless transmission technology. According to the different transmission media, it can be divided into magnetic resonance wireless energy transmission technology and electric resonance wireless energy transmission technology. The technology uses resonant body that has the same resonance frequency, when separated by some distance it can realize energy transmission by resonance with magnetic or electric fields as media interaction, and belongs to the revolutionary wireless energy transfer technology.

2. Basic Principle of Magnetic Coupling Resonance Wireless Energy Transmission

The technology of wireless energy transmission based on magnetic coupling and resonance takes advantage of two electromagnetic systems with same specific resonance frequency, which can excite resonance due to electromagnetic coupling, to transfer energy in a certain distance. Generally speaking, two electromagnetic systems in a certain distance is weakly coupled. However, if the two systems' natural resonant frequency are the same, they can excite strong magnetic resonance. If one of them provides energy for the system constantly, and the other side consumes energy simultaneously, the energy transmission could be realized.

Different from the inductive wireless transmission and the microwave radio transmission, wireless energy transmission system of the magnetic coupling resonance, which utilizes the principle of resonance to transfer the energy transmission from the transmitting terminal to the receiving terminal, is like a space shorted. The energy transferred from the lowest loss path, so that the energy doesn't radiation into the air like a microwave wireless transmission.

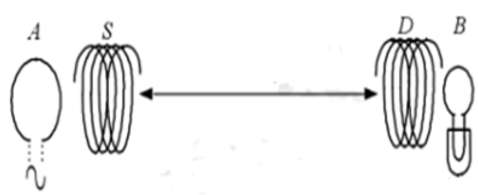

Figure 1. Schematic Diagram of MIT's Wireless Energy Transmission System of Magnetic Coupling Resonance

Figure 1 shows the schematic diagram of an energy transmission system of the magnetic coupling resonance. The energy receiver of D and the emission source S take advantage of the induction coil with the same resonance frequency. The emission source generates an alternating magnetic field as the oscillation circuit stimulate induction coil generates an alternating magnetic field. When the induction coil of the receiving terminal goes into the magnetic field that have the same resonant the frequency, generated magnetic resonance in the receiving coil, in the receiving apparatus the energy constantly gathering to supply to the load ,so energy transmission achieved. Theoretically the emitting source can supply energy to multiple receiving apparatus in the effective area, while the other systems are unaffected or in very weak influence out of this specific resonance frequency.

3. Characteristics of Magnetically Coupled Resonance based Wireless Energy Transfer Proposed by the MIT

The key of the wireless energy transmission technology which MIT called Witricity is the use of non-radiation magnetic coupling that can produce a very strong mutual coupling between two coils with the same resonant frequency. Common magnetic coupling is only used for short-distance range, which requires the device is very close to the induction coil, as the magnetic energy decays rapidly with the increasing distance from the power or charge, and thus in the conventional magnetic induction distance can only increase by enhancing strength of the magnetic field.

Unlike the conventional method, Witricity adopts the matched resonant antenna. The magnetic coupling can occur within a distance of a few feet and does not need to enhance the strength of the magnetic field. Though power transfer by electromagnetic wave thought wireless has a longer transmission distance, transmission power only a few micro-watts to a few mill watts. The energy transfer by Witricity resides in the resonant field, unlike electromagnetic radiation which wastes a lot of energy on the radiation.

Researchers of MIT believe their found is a new method of wireless energy transfer, i.e., non-radiation electromagnetic resonant tunneling effect. In the microwave region, for example, a horn waveguide generates an attenuation electromagnetic wave, also called evanescent wave, disappears wave, *etc*. If reception waveguide support the electromagnetic wave mode of corresponding efficiency, i.e. attenuation field propagating wave mode, the energy can transfer from one medium to another media by tunnel transmitted from. In other words, the evanescent wave coupling is a concrete manifestation of tunnel effect in the electromagnetic field. In essence, the process is as same as the quantum tunnel effect, but electromagnetic waves instead of wave function in quantum mechanics. In order to distinguish them from ordinary electromagnetic induction coupling, this method also called resonance of the magnetic coupling, [1].

The research of magnetically coupled resonant wireless power transmission by MIT has epoch-making significance, while achieving a wireless energy transmission system has the following two characteristics:

3.1 Integration Resonance Technology

The wireless energy transmission system based on the electromagnetic induction coupling which takes advantage of hundreds of turns of a coil tightly wound, barely able to obtain more than 50% of the transmission efficiency of a distance of several mm. In about 2m the transmission efficiency of MIT's system of the transmitter coil and the receiver coil only wound 5.25 circle crude copper is approximately 40%, when the distance is 1m the transmission efficiency can be up to 90%. It shows that different from electromagnetic induction coupling with wireless energy transmission, magnetically resonant wireless power transmission technology integration resonance technology can achieve efficient energy transmission in the middle-distance.

3.2 The Use of the Character that Magnetic Near Field does not Spread to the Distance

For an electromagnetic field emission source, alternating electromagnetic field in the surrounding space can be divided into two different parts: the near field (also known as induction field) and far field (also known as the radiation field). The electromagnetic field energy of the former periodically flow back and forth between the surrounding space and the generating source of the generating source, and is not emitted outside, while the electromagnetic energy of the latter emits outside by the form of electromagnetic waves. Paper [3] gives the method to devise that, but they do not have clear boundaries. In general, the range around presence source for the center of $\lambda/2\pi$, is called the near field [4].

In the near field around the emission source, the electromagnetic field energy flows back and forth periodically between the surrounding space and the generating source of the generating source, and is not emitted outside (if there are no resonance near the receiving device). There is not an accurate proportional relationship between the strength of electric field and magnetic field in the near field, while the proportional relationship in the far-field region of the electric field strength E and the magnetic field strength H is determined [4].

The electromagnetic wave had already widely used in communication technology for long time. In the contrast, the near field energy transfer is considered as one of the main reasons of electromagnetic interference that should be restrained.

However, the researchers from MIT maximized the advantages of near-field and developed a wireless energy transmission system. Seemingly, it much likes the electromagnetic induction based energy transmission, but in fact, the fusion resonance technology is completely different from electromagnetic induction. MIT's wireless energy transmission system can generate electromotive and the intensity is proportional to the variation of the magnetic flux through the coil internal [1], the transmission of energy is far over the Faraday's law of electromagnetic induction.

When using the non-contact power transmission based on electromagnetic induction, the transmission efficiency can barely obtain about 60% at the distance of several mm. However, the transmission efficiency of MIT's system is approximately 40% at 2m and the efficiency can achieve high of approximately 90% at 1m, at the same time the transmitter/receiver coil is only five laps crude copper. It shows that different from the electromagnetic induction, the technology does not rely solely on the intensity of flux.

4. Theoretical basis of Magnetically Coupling Resonant Wireless Energy Transfer

The phenomenon of resonance existed widely in the nature, such as the sound of the instrument resonance, animal ears basement membrane resonance, circuit resonance *etc*. MIT's researchers believe that the coupled resonator system formed with object of the same resonant frequency (such as sound, electromagnetic field, nuclear, etc.) can exchange of energy with high efficiency. Relative to other media, the magnetic field is more suitable for the application of life, so electromagnetic resonance that regard time-varying magnetic field as coupling medium has been proposed to achieve wireless energy transmission [1].

The system shown in Figure 1 contains two parts: respectively transmitting and receiving terminals. The emission terminal formed of transmitting circuit A and the source resonant coil S; the receiving terminal formed of the resonant received coil D and the load circuit B. The work process is as follow: as an excitation source transmitting circuit A generates the medium-high frequency magnetic field, the source resonant coil S resonances under excitation, energy transfer from A to S by coupling, energy transfer from S to coil D of the reception side by magnetic coupling resonance, D coupled with the circuit of load B to achieve energy transmission. All four coils A, S, D and B were designed so as to have the same resonant frequency that can generate resonance in the magnetic field. Due to the different functions, the other parameters of the respective coils are not identical, such as the quality factor, shape, dimensions, etc. In this structure, the coupling between the A and S close coupling, and so as D and B, while between S and D is the distance coupling.

The coupling between two general LC circuits with a certain distance is weak. However, if both of them have the same natural resonance frequency, when they operate at the resonant frequency and to meet certain necessary conditions the two coils could produce resonance and generate strong coupling. If a plurality of coils having the same resonant frequency work at the same time, then the energy is re-allocated according to the degree of coupling. If a terminal is connected to the power supply to provide energy continuously to the resonant system (Figure 1 A) and the other parts consume energy (Load B), effective transmission of energy is achieved.

The reason that it is called "magnetic coupling resonance" is that the exchange carrier of energy in space is an alternating magnetic field, the electromagnetic resonator of each of the coils is realized by the magnetic field in the coil and the electric field of distributed capacitance and energy transfer in space is achieved by resonance. The characteristic of this method is the addition of the transmission and reception of the self-resonant coil of the high quality factor resonance system in the transmitting and receiving circuit.

At present, there are three main theories to analyze the magnetic coupling resonance wireless energy transmission system: the MIT's couple-mode theory [1, 2], the scattering matrix theory [5] and circuit theory [6]. MIT uses couple-mode theory [1, 2] to analyze the efficiency of the magnetic coupling resonance wireless power transmission system and believes that when both of emission and receive coils achieve resonance the efficiency is maximum. As the couple-mode theory is very complex, papers [7~12] use circuit theories to analyze the system and verified that the circuit models are suitable for analyzing the system. The couple-mode theory and the scattering matrix theory are very difficult to be received, so the most researchers from engineering background mainly take circuit theories to analyze the technology.

4.1 MIT's Couple-mode Theory

In the embodiment of the energy transfer, the system of two loops with the same resonance frequency is able to transfer the energy effectively, and for other non-resonant things energy loss is small. In resonant coupling system, there is a strong coupling region can be utilized, and in the strong coupling region of the given coupling system, the energy can transfer effectively between the resonance body by the resonance. In this way, the power transfer can be achieved almost omnidirectional and efficient, regardless of the impact of the size of the object in the surrounding environment and can reduce the loss caused to the minimum.

Couple-mode theory is used to study the general laws between two or more coupling electromagnetic wave mode. It can be used to model the resonance system with any number of resonance bodies, as long as weak coupling between each resonance bodies exists. For any complex resonance system, couple-mode theory can be used to build an analytical framework simply, intuitively and accurately. Couple-mode theory has become the main analytical tools to study the coupling between the electromagnetic wave modes.

Couple-mode theory is used to solve the problem like this: First, do not take coupling into consideration, divide a complex coupled system into a certain number of isolated parts or units, correctly solving the movement equation group of isolation unit, write the coupled equation group as the form of normal modes, and normalize the mode or wave amplitude, so that they can represent the energy or power of the mode; then considering the coupling and assuming that the original complex system is composed of certain isolated cells mutual coupled, so that the state of each motion of a cell has a disturbance in this coupling, the coupling equations is expressed by the mode amplitude of the element without coupling.

The MIT application couple-mode equation established the mathematical model of the magnetic coupling resonance wireless energy transmission system (The resonant coil S and D of figure 2) [1, 2]:

$$\dot{a}_m(t) = (i\omega_m - \Gamma_m)a_m(t) + \sum_{n \neq m} i\kappa_{mn} a_n(t) + F_m(t) \qquad (1)$$

In equation (1), is resonance body (resonance coil), the energy of the resonance coil is, m represent different resonance body,; is the resonance angular frequency of m; is decrement of loss which caused by heat loss and radiation loss,, is the coupling coefficient between the resonance body of m and n.

4.2 Circuit Theory

MIT's researchers are using the couple-mode or extension theory to analyze magnetically coupling resonance systems. It is so different from the actual circuit, which makes it very difficult for the researchers from electric engineering background to understand. Couple-mode theory is more suitable to describe the energy change of the system at the state of the resonant coupling. Circuit theories, such as the lumped parameter circuit rules are more suitable as an adjunct to simplify the analysis of system performance [12].

4.2.2 Circuit Model and Equivalent Circuit Diagram

According to lumped parameter method of the circuit theory [10], it takes advantage of the circuit inductance, mutual inductance to analyze the energy transfer process of the magnetic coupling resonance wireless energy transmission system shown in Figure 1 and draws the equivalent circuit diagram as shown in Figure 2:

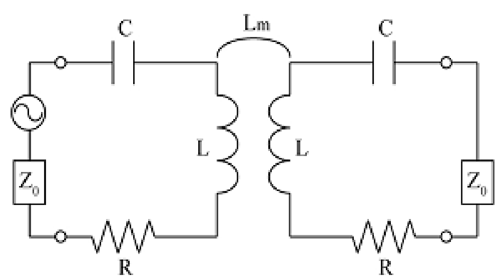

Figure 2. Equivalent Circuit Diagram of the Resonant Magnetic Coupling Wireless Energy transmission System

In figure 2, L, C, R, respectively, represent the resonant coil of the resonant inductor, resonant capacitor and the resistance of resonant coil; represented as the mutual inductance between the two resonant coils of the resonance body to express the coupling relationship between the resonance body, such equivalent circuit diagram lay the foundation for using the circuit theory to analyze wireless energy transmission. As the equivalent circuit in paper [10] doesn't take the impedance of load of the reception side into consideration, therefore, based on this there emerges a variety of modified equivalent circuit diagrams [7~13].

4.2.3 The Quality Factor Q and Transmission Efficiency

The quality factor of the resonant circuit is of great importance. Its physical definition *t* is the ratio of the stored energy of the resonant circuit and the energy consumed by the load each cycle multiplied by 2, i.e, . The higher of the quality factor, the smaller of the load on the energy consumed in ever period, the greater of the energy that can be transmitted.

In circuit theory, only the resistance consumes energy, while the inductor and the capacitor do not result in energy loss. They just continuously store and release energy. When the input voltage or input current of the circuit is constant, the reactive power in the circuit is very large if the reactance of the circuit is large, thereby the output power and efficiency of the system reduced. The reactance of the circuit would be zero when the circuit is in resonance state. In magnetic coupling resonance wireless energy transmission system, the transmitter circuit achieves resonance state when the transmitter circuit reactance is 0 or approaches 0; as the same, the reception circuit reaches the resonant state when the reception circuit reactance is 0 or close to 0.According to [14, 15], only if the transmitting circuit and the reception circuit achieve resonance at the same time, the efficiency of the wireless transmission system is maximum.

5. The Research Progress of the Magnetic Coupling Resonant Wireless Power Transmission

5.1 Circuit Theory

Different from MIT's "couple-mode theory", the study from University of Tokyo is based on antenna theory, circuit theory and electromagnetic field calculation. They seek the best frequency bands and transmission efficiency [16] and study the relationship of the two different self-resonance characteristics of the helical coil (open-type and short-circuit-type) and the wireless energy transfer efficiency [17] based on the electromagnetic field analysis and simulation. Their paper [17] points out that the open circuit coil is equivalent to the series resonance, the transmission efficiency is higher; the short circuit coil is equivalent to the parallel resonance, at the resonant frequency input impedance is infinite, the transmission efficiency is low. And they also study about the two coils are connected in series and the rows of the parallel resonant capacitor, obtain that on the appropriate parameter conditions the short circuit coil series capacitor can be obtained greater transmission efficiency at a relatively low operating frequency.

In order to make the magnetically coupling resonant wireless power transmission technology to achieve higher transmission efficiency and farther transmission distance, the operating frequency is generally in level of MHz's. However, the available frequency band is limited by ISM frequency range. The available frequency range is very narrow. For example, according to the ISM, the frequency range is only 13.65 MHz ± 7 kHz at the 13.56MHz.

To further develop the value magnetic coupling resonant wireless energy transmission technology. Based on the method of the impedance matching network, [18] adjusts the system resonant frequency to make it suitable for the available frequency range of ISM. Paper [19] studies method of maximizing transmission efficiency in certain transmission distance further, by calculating and simulating the characteristic impedance, coupling coefficient, coil loss resistance and resonant frequency parameters, obtaining the conditions to maximize efficiency .

5.2. Three-coil Energy Transfer System

In March 2009, MIT proposed a new mechanism of energy transmission which is different from the traditional system contains two resonance coils energy transfer in paper [20] that by adding a third coil which has the same resonance frequency into the transmission path as the media to improve the efficiency of the energy transmission system . The system diagram is shown in Figure 3:

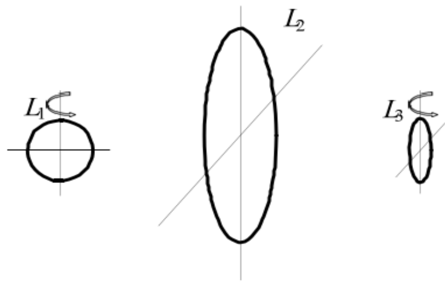

Figure 3. Diagram of Three-coil Energy Transfer System

Source coil L_1 and the receiving coil L_3 is always maintained vertically, and rotate with the same angular frequency, between them there doesn't exist directly magnetic coupling, however, it transfers energy through the intermediate coil L_2 and the strong coupling of both sides of the coil . Adjusting the period of rotation of the both sides of the coil appropriately, so that the addition of coupling energy of the both sides of the coil and the intermediate coil is zero. The transmission efficiency of the system will increase from 29% to 61.2%.

5.3 The Energy Transmission of Multi-receiving System

MIT has published the article [21] which is about the synchronized power supply system of middle distance with several receivers in January 2010. The article [21] uses a large transmitter coil (area of 1 m^2) to transfer energy to two small receiving coils (each probably $0.07m^2$) at the same time, studies about the impact of the multi-receiving body to tune and energy transfer efficiency of the system , the size of the system is shown in Figure 4.

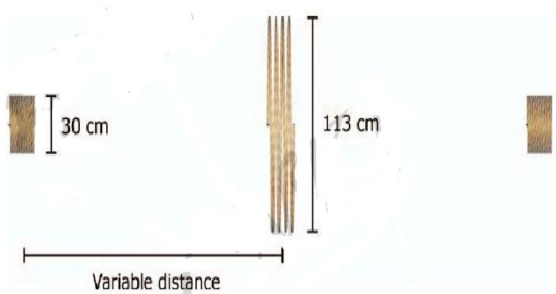

Figure 4. The Diagram of the Multi-receiving System

The theoretical analysis and experimental results show that if two receivers work simultaneously the efficiency is higher than each receive works alone. This conclusion is also applicable to the receives body is more than two.

5.4 Four-coil Energy Transfer System

University of British Columbia regards biomedical sensor as application background and study about applications and optimization of magnetic coupling resonant wireless power transmission technology in small power [22, 23].

Paper [22] takes the structure of four-coil energy transfer system, includes four energy transmission coils having the same natural frequency , the transmitter end composed by resonant body 1 and 2 , the distance between them is very close, resonance body 1 directly connected with the power, which can reduce the impact of the resistance of power on the resonance body 2;receiving end composed by resonance body 3 and 4, the resonance body 4 is directly connected with loads, which can also reduce the impact of load to quality factor of resonant body 3.

Paper [22] analyses the system from the point of the circuit theory and obtains the expression of the received power and transmission efficiency. Based on that, it analyzes the impact of the quality factor of each of the coils, the source resistance and the load resistance on the energy transfer efficiency and obtains the general conditions to maximize the transmission efficiency within a certain distance. Since the high quality factor is a necessary condition of the high efficiency, the paper gives the general methods of making the coil by using a multi-strand designed to obtain the highest quality factor. Finally, it establishes an energy transmission system, as shown in Figure 5, the coupling coefficient between the drive coil and the concentric primary coil is 0.56, the outer diameter dimension is 64mm; the coupling coefficient between the secondary coil and the concentric load coil is 0.59, the diameter size is 22mm, the thickness is only 2.5mm, which only equals to a Canadian dollar cents size.

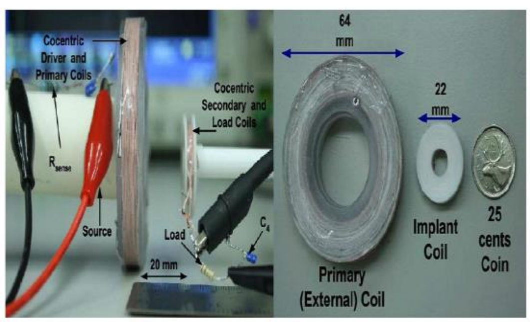

Figure 5. The Diagram of the Multi-receiving System

When the load is a resistance of 100Ω and the transmission distance is 20mm, the transmission efficiency is about 83%. When the transmission distance is 32mm, the transmission efficiency is about 72%. The experimental results are consistent with the theoretical analysis, so it verifies that four-coil energy transfer system is better than the two-coil energy transfer system.

Based on the circuit theory, Electronics and Telecommunications Research Institute of Korea analyses the conditions to maximize the efficiency of the magnetic coupling wireless energy transmission system that has four coils and study on the performance of multi-receiver body systems in papers [24-26] preliminary.

5.5 Adjustable Frequency Resonance Body

In papers [27-29], University of Pittsburgh uses MIT "witricity" technology to build a frequency adjustable wireless energy transmission system to supply to biosensors and implantable devices, valid feasibility in the air and the simulation model of the human brain.

The fabrication process of the resonance transceiver device that paper [27] used is shown in

Figure 6, where A is the core, which is for changing the inductance value of the coil B, the capacitor is constituted by two semi-circular sheet, we can adjust the capacitance value by adjusting the two semicircles the overlapping area.

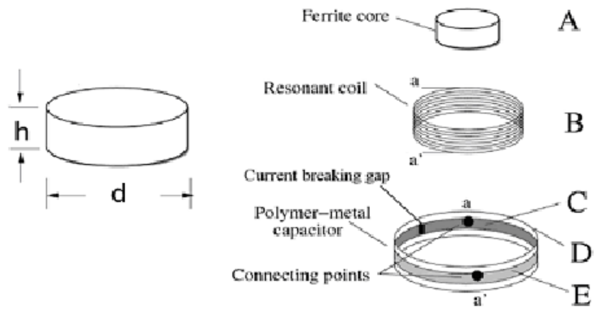

Figure 6. Frequency Adjustable Resonance Bodies

In order to reduce the loss of the thermal resistance, the coil and capacitor of the receiving end are produced by silver, the diameter of transmitter side is 165mm, and the diameter of receiving end is 41mm. When the transmission distance is 90mm, the transmission efficiency is 22.3%.

Paper [29] study about using magnetic resonance wireless energy transfer technology to supply for body sensor network, when the transmission distance is 15cm, the transmission efficiency is 80%. In addition, if the center of the receiver and the transmitter coil is biased, it may has some impact on energy transfer.

In the research of the University of Pittsburgh, the volume of the receiving end are generally small and compact design, which is very suitable for implantation. However, its theoretical analysis is based on MIT's couple-mode equation, it uses light-emitting diodes as the receive load, which can only receive lower energy and not be a good equivalent sensor load.

5.6 Adaptive FM and Frequency Splitting Phenomenon

Based on the circuit theory, Joshua R. Smith and other people from the University of Washington analyzes the frequency splitting, the best transmission distance (critical coupling points) and detuning phenomenon of magnetically coupled resonant wireless power transmission system. They propose that the adaptive FM technique can compensate for the transmission distance, and finds the impact on the efficiency of the orientation change of coil. The experiments show that after using that technology the system can still maintain the efficiency of more than 70% as the receiving coil can change in any orientation within the transmission range of 0 ~ 70cm[30]. Finally, it establishes a wireless energy transmission system to supply for a laptop wirelessly, as shown in Figure 7.

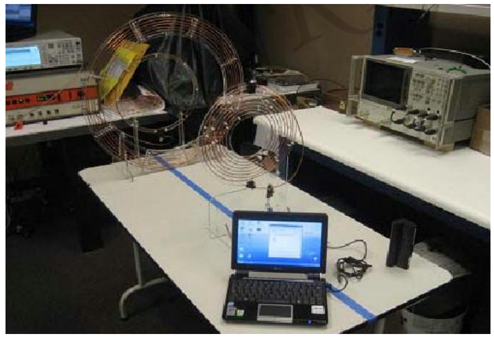

Figure 7. Adaptive FM Technology Supply for a Laptop Wirelessly

Seth Copen Goldstein Carnegie and other researchers from Mellon University study the feasibility and the circuit theoretical of using an emission source coil to supply for multiple small receivers at the same time [31]. In [31] the theoretical takes the coefficient of mutual induction between all coils, and explains the frequency splitting phenomenon at strong coupling from theoretical and experimental. In the experiment, when the load of the receiving coil is 100 ohm and in the center of the coil, the power received is 28.5mW.

5.7 Loss Distribution

In [32] ,University of Wisconsin achieves to transfer a power which is 220W wirelessly about 30cm by using resonant magnetic coupling technology ,the transmission efficiency is 95%.Then it analyses the loss distribution in the system , after the comparison of the different linear AC resistance it proposes a new line structure to reduce the heat loss of the coil.

5.8 New Material

In [33-34], Japan's Mitsubishi Electric Research Institute proposes the method that with a negative refractive index material to improve wireless energy transfer efficiency of the magnetic resonance from the theory and simulation, negative refractive index material permittivity and permeability are both negative, between the transmitting and receiving coils were placed on a flat plate made by the two negative refractive index material, as shown in Figure 11. And a negative refractive index material can amplifying the evanescent wave and enhance coupling strength of evanescent wave at a fixed distance, thereby the efficiency of energy transfer improved.

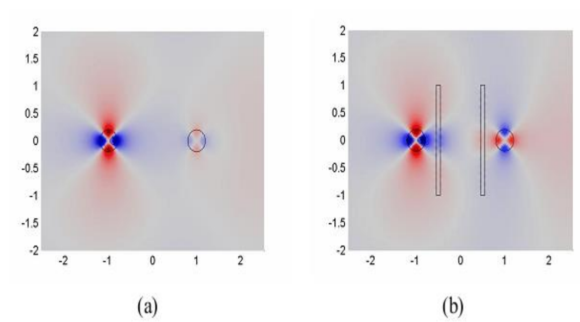

Figure 8. The Electric Field Distribution Figure of Two Coupling Insulating Resonant Body
(a) Not add a Tablet of Negative Refractive Index Materials
(b) Add a Tablet of Negative Refractive Index Materials

5.9 Lumped Parameter Method and Dipole Analysis

Since 2008,a team of Harbin Institute of Technology which is leaded by Zhu Chunbo starts the basic research about magnetically coupled resonance technology [35-37]. Paper [35] analyses the circuit topology of Intermediate frequency resonance system by using circuit theory and electromagnetic field theory, they find the conditions to maximize the current of the receiving end. The experiments using lumped parameter to found a resonance body, which can transfer energy of 23W in at transmission distance of 70cm. Text [36] designs a simple wireless energy transmission device ， simulates and analyses characteristics of the back electromotive of receiving coil under different operating frequency and different transmission distance. The results of experiments show that the system can pass the maximum power of up to 50W, the efficiency can achieve higher than 60%, and the transmission distance is more than 1m. Based on the analysis of magnetic dipole, paper [37] establishes the coupled coil system model, calculates the radiation level of the typical coil, reveals the quantitative relationship between the received energy and resonance parameters, and gives the conditions of matching parameters to maximize energy of load. In addition, they study the method to improve the transmission power, the transmission distance. On the basis of in-depth analysis of the transmission mechanism, they give the general design method of energy transmission system, and make a preliminary exploration of the applying of magnetic resonance technology in multi-receiving end system.

5.10 Mutual Inductance Coupling and Frequency Tracking

A team of South China University of Technology led by Professor Zhang Bo research about mutual inductance coupling model [38]; analyze the working principle of the resonant coupling based on the circuit theory, obtains the mechanism and relationship between the transfer efficiency with distance, frequency, coil parameters; proposes the method to obtain the conditions to maximum transmission efficiency and optimize the design, and verified them by experiment.

Due to the energy transfer efficiency in the experiments on the frequency is very sensitive to changes, when the inductance of transmitter coil change a little, the transmission efficiency will decrease a lot. In order to compensate for this change, they employ frequency tracking control method to design a system which can adjust the emission frequency automatic, so the transmission side is always working at the resonance point that can ensure the level of the transmission efficiency. Experiments show that the method can ensure the efficiency of the transmission system well.

5.11 Other Developments

In addition, based on MIT' research the team of Southeast University did the theoretical and mathematical derivation, and verified them by experiments [39]. Zhongshan University took advantage of weak inductive coupling principle, developed a low-power wireless energy transmission system, and demonstrates the advantages of using multiple strands coil, when the experimental system input power 1W, the light emitting diode could be lit outside 4m, and the transmission efficiency is 10% [40]. Overall, compared the domestic research in magnetic resonance wireless energy transmission to abroad, it was basically still in the theoretical stage, the power levels of the designed experimental system was very low and far from the practical.

6. Problems and Future Research

Magnetically coupled resonant wireless power transmission technology is a new field that both academia and industry from all over the world start to explore. The multidisciplinary basic research and applied research that cross set of electromagnetic fields, power electronics, high-frequency electronic, electromagnetic induction and coupling theory, and belongs topics at the forefront of the field of the world's energy transport. As the couple-mode theory which proposed by MIT is not close to the actual circuit, difficult to understand and lack of theoretical support, the use of circuit theory to study the mechanism of magnetic coupling resonance wireless energy transfer technology has become the mainstream methods. MIT uses microscopic field of quantum mechanics radiated electromagnetic energy resonant tunneling effect inherent mechanism to explain this wireless energy transfer, which belongs to the combine of classical theory and non-classical theory, and not entirely convincing.

The next study will focus on the combination of a variety of theoretical, and further explore the energy transfer mechanism based on magnetically coupling resonant wireless power transmission technology. In terms of practical, in order to improve the transmission distance and efficiency of the magnetic coupling resonance wireless energy system, the key lies on designing and producing a coil with a high Q value, and the maximum efficiency of the resonant frequency matching. As the calculation of the existing energy transmission coil rarely involved in antenna theory, fabrication methods is mostly wound coil, the process is difficult to guarantee the production of coils and consistent to the theoretical calculations, thereby affecting the distance and efficiency of wireless energy transmission. Therefore, about how to improve the Q value of the coil above, we need further study, such as on the coil material, production process, calculation methods and antenna theory.

Magnetically coupled resonant wireless power transmission technology is a new energy transmission technology, which can effectively overcome the problem that existed in wired power supply equipment ,such as can’t move flexibility ,unsightly environment ,easy to contact with sparks, supply line exposure ,and especially suitable for mobile devices, inflammable and explosive environment, underwater, safe power supply of oilfield down hole equipment. The technology not only has important applications in the field of electric vehicles, industrial robotics, aerospace, military, oil fields, mines, underwater operations, wireless sensor networks, and also widely used in household appliances, RFID, medical devices and other civilian areas prospects. So it is very important to have a breakthrough on magnetically coupled resonant wireless power transmission technology basic theory and practical aspects.

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