International Journal of Power Control and Computation(IJPCSC)
Vol .7. No.1 – 2015 Pp. 11-20
©gopalax Journals, Singapore
available at : www.ijcns.com
ISSN: 0976-268X

AN ANALYSIS OF WI-FI POWER TRANSMISSION USING HRC

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ABSTRACT

In this paper, current developments and research progress in the High Resonant Coil (HRC) area are presented. Advantages of HRC are analyzed by comparing it with the other wireless power transfer (WPT) technologies, and different analytic principles of HRC are elaborated in depth and further compared. The hot research spots, including system architectures, frequency splitting phenomena, impedance matching and optimization designs are classified and elaborated. Finally, current research directions and development trends of HRC are discussed.

Index Terms— wireless power transfer; strongly coupled magnetic resonances; mid-range non-radiative high-efficient power transfer

I. INTRODUCTION

In 2007, wireless power transfer shocked the world again, they proposed high resonance coil (HRC), and they were able to transfer 60 watts wirelessly with ~40% efficiency over distances in excess of 2 meters [5]. Subsequently, Intel and Qualcomm also demonstrated their wireless power transfer systems, which indicated that this novel technology would soon appear in our daily life.

So far, wireless power transfer technology can be roughly classified into three kinds in accordance with the working principles, which include electromagnetic radiation mode, electric field coupling mode and magnetic field coupling mode. In electromagnetic radiation mode, electric energy is generally converted into electromagnetic energy like microwaves or laser beams which can be radiated outward, then be received and converted back into electric energy with using a silicon rectifier antenna in the receiver. Because of its high power density and good orientation features, electromagnetic radiation mode is usually suitable for the long distance transfer applications, especially for the space power generation or military applications.
However, its transfer efficiency is severely affected by the meteorological or topographical conditions, and the impacts on creatures and ecological environment are unpredictable. A high-frequency and high-voltage driver source excites the resonant transmitter to generate an alternating electric field which can couple with the resonant receiver. Energy will be delivered as soon as this coupling relation is set up. The transfer efficiency of this mode is affected by surrounding objects [6,7], and the transfer power is relatively low, but if corresponding treatments are done beforehand, the electric field coupling mode will find suitable applications. In summary, microwaves and lasers dominate in the long-range wireless power transfer applications, and electromagnetic induction dominates in the short-range wireless power transfer applications. As a novel and burgeoning technology, HRC fills exactly the void in the mid-range wireless power transfer applications.

II. PRINCIPLE ELABORATION

2.1. Coupled Mode Theory

CMT aims to research the laws in the coupled modes of electromagnetic waves, which was originally applied in the microwave field. According to CMT, the physical processes of power transferring from one resonant object to another can be described as:

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

where indices denote different resonant objects, $a_m(t)$, ω_m, Γ_m, K_{mn}, and $F_m(t)$ represent the modal energy amplitude, the resonant angular frequency, the intrinsic decay rate, the coupling coefficients and the driving terms,

$$\begin{cases} \dfrac{da_m(t)}{dt} = (i\omega_m - \Gamma_m)a_m(t) + iK_{mn}a_n(t) + F_m(t) \\ \dfrac{da_n(t)}{dt} = (i\omega_n - \Gamma_n - \Gamma_L)a_n(t) + iK_{nm}a_m(t) \end{cases}$$

respectively. If the intrinsic decay rate is not considered, the energy exchange between two resonant objects will be lossless. When considering the loss during the energy exchange,we use:

(2)

where Γ_L represents the additional energy decay rate due to the load. Suppose that the properties of these two resonant objects are identical, then ω_m and ω_n equal ω_r, K_{mn} and K_{nm} equal K, and make the driving terms $F_m(t)$ be $Ve^{i\omega t}$ simultaneously, Equation (2) can be re-written as:

$$a_m(t) = \frac{\left[(\Gamma_n + \Gamma_L) + i(\omega - \omega_r)\right]Ve^{i\omega t}}{K^2 + (j\omega - j\omega_r + \Gamma_m)(j\omega - j\omega_r + \Gamma_n + \Gamma_L)} \quad (3)$$

$$a_n(t) = \frac{iKVe^{i\omega t}}{K^2 + (j\omega - j\omega_r + \Gamma_m)(j\omega - j\omega_r + \Gamma_n + \Gamma_L)}$$

The transfer efficiency and transfer power expressions in CMT can be described as follows [5]:

$$\eta = \frac{\Gamma_L |a_n(t)|^2}{\Gamma_m |a_m(t)|^2 + (\Gamma_n + \Gamma_L)|a_n(t)|^2} \quad (4)$$

$$P_L = 2\Gamma_L |a_n(t)|^2 \quad (5)$$

By substituting Equation (3) into Equations (4) and (5), the transfer efficiency and transfer power expressions can be rewritten as Equations (6) and (7):

$$\eta = \frac{\Gamma_L K^2}{\Gamma_m[(\omega - \omega_r)^2 + (\Gamma_n + \Gamma_L)^2] + (\Gamma_n + \Gamma_L)K^2} \quad (6)$$

$$P_L = \frac{2\Gamma_L K^2 V^2}{[K^2 + \Gamma_m(\Gamma_n + \Gamma_L) - (\omega - \omega_r)^2]^2 + (\Gamma_m + \Gamma_n + \Gamma_L)^2(\omega - \omega_r)^2} \quad (7)$$

Assume that this system works in resonant state, the driving angular frequency ω equals the resonant angular frequency ω_r. By taking the derivatives of Equations (6) and (7) with respect to K and Γ_L, the optimization conditions which maximize the transfer efficiency and transfer power can be obtained as follows:

$$\left.\begin{aligned} \Gamma_{L\eta_{\max}} &= \Gamma_n \sqrt{1 + \frac{K^2}{\Gamma_m \Gamma_n}}, \\ \Gamma_{LP_{L\max}} &= \frac{K^2 + \Gamma_m \Gamma_n}{\Gamma_m}, \\ K_{P_{L\max}} &= \sqrt{\Gamma_m \Gamma_n + \Gamma_m \Gamma_L} \end{aligned}\right\} \quad (8)$$

The derivative of Equation (6) with respect to the coupling coefficient K cannot equal zero, because the intrinsic decay rate is not zero. This means that there is not an optimized K which can maximize the transfer efficiency. So we can conclude that the closer the distance, the higher the efficiency. But it is only based on the premise that other variables should be all fixed.

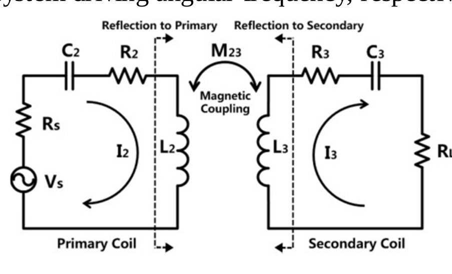
In non-resonant state, the system driving angular frequency ω does not equal the resonant angular frequency ω_r. Assume that the energy decay rate and coupling coefficient are constant, the derivative of the transfer efficiency η with respect to the driving angular frequency ω is nonexistent. This indicates that the maximum transfer efficiency can be achieved only in the resonant state. Similarly, by taking the derivative of the transfer power P_L with respect to the driving angular frequency ω, the optimization conditions based on maximizing the transfer power can be obtained as Equation (9), which indicates that the frequency splitting phenomenon appears [11]:

$$\omega = \omega_r, \ \omega_r \pm [K^2 - 0.5\Gamma_m^2 - 0.5(\Gamma_n + \Gamma_L)^2]^{0.5}$$

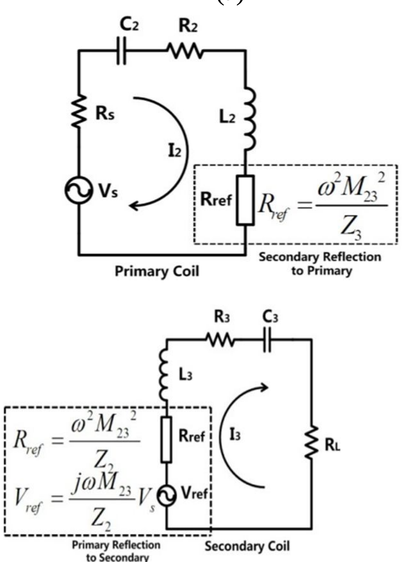
2.2. Circuit Theory

The concept of coupled mode in electromagnetics may be traced back to the early 1950s, and after a long period of development, the current CMT is suitable for analyzing the energy exchange process between two resonators [84], but its concepts are obscure. Rather, CT based on mutual inductance model is more straightforward.

Parallel-parallel and series-series compensations are the basic structures which have been well discussed in the literature, and additionally, their analysis and design methods are elaborated in [34,35]. For simplicity, this paper only takes the series-series compensation as an example to demonstrate CT. Figure 1a shows the equivalent circuit model of a system architecture with two coils, in which, R_S, R_2(R_3), L_2(L_3), C_2(C_3), M_{23} and R_L represent the internal resistance of the voltage source, the coil parasitic resistances, the coil self-inductances, the resonant capacitors, the mutual inductance and the load resistance, respectively. Figure 1b,c explains the simplified circuit models of Figure 1a by using the bidirectional reflectance impedance analysis (BRIA) method, where V_{ref}, R_{ref}, Z_2(Z_3) and ω represent the reflected voltage source from the primary coil to the secondary coil, the reflected impedance from the secondary coil to primary coil, the primary (or secondary) coil total impedance and the system driving angular frequency, respectively.



(a)



(c)

***Figure 1. (a)** Equivalent circuit model of system architecture with two coils; **(b)** simplified circuit model by making the secondary coil to be the equivalent impedance in the primary coil; **(c)** simplified circuit model by making the primary coil to be an equivalent voltage source and the equivalent impedance in the secondary coil.*

Take the model shown in Figure 1b for example, if the system is in the resonant state, the reflected impedance from the secondary coil to the primary coil, the transfer efficiency and the transfer power can be drawn as[34,35]:

$$R_{ref} = \frac{\omega^2 M_{23}^2}{R_3 + R_L} \quad (10)$$

$$\eta = \frac{\omega^2 M_{23}^2 R_L}{(R_3 + R_L)[\omega^2 M_{23}^2 + (R_2 + R_s)(R_3 + R_L)]} \quad (11)$$

$$P_L = \frac{\omega^2 M_{23}^2 V_s^2 R_L}{[\omega^2 M_{23}^2 + (R_2 + R_s)(R_3 + R_L)]^2} \quad (12)$$

By taking the derivatives of Equations (11) and (12) with respect to M_{23} and R_L, the optimization conditions based on maximizing the transfer efficiency and transfer power can be obtained using Equation (13). We can find that the optimization load values for both the maximum transfer efficiency and maximum transfer power can be determined when the mutual inductances are fixed, but they are not identical. There is also an optimized mutual inductance value for maximizing the transfer power when the load is fixed. But the derivative of the transfer efficiency with respect to M_{23} is non-existent, which is the same as the analysis result of CMT. Therefore, the conclusion can be drawn that the transfer efficiency increases with the decreasing distance.

However, if the load is not fixed, to realize the highest efficiency, the corresponding optimization conditions shown in Equation (13) should be satisfied:

$$R_{L\eta_{max}} = \sqrt{\frac{\omega^2 M_{23}^2 R_3}{R_2 + R_s} + R_3^2}, \quad R_{LP_{L\max}} = \frac{\omega^2 M_{23}^2}{R_2 + R_s} + R_3,$$
$$M_{P_{L\max}} = \frac{\sqrt{(R_3 + R_L)(R_2 + R_s)}}{\omega} \quad (13)$$

Although the system analysis process is a little more complicated in the non-resonant state due to the emergence of additional imaginary power, the bidirectional reflectance impedance analysis method is still applicable. In this situation, the concept of power factor should be introduced to evaluate the amount of the imaginary power. Besides, the frequency splitting phenomenon based on maximizing the transfer power happens in the non-resonant state, and two frequency splitting points maximizing the transfer power appear. As the driving frequency changes, the transfer efficiency will also change, but it should be noted that the transfer efficiency is always maximal in the resonant state, which is the same as the analytical conclusions of CMT.

III.Classification and Elaboration of Hot Research Spots

3.1. System Architectures

In practical applications, the transfer distances and load impedances frequently change. According to the analysis in Sections 2.1 and 2.2, we can find that the system architecture with two coils can't satisfy these requirements, so the study of novel system architectures is valuable. The system architectures with three and four coils can optimize the transfer characteristics with additional adjustment freedom degrees. Besides, the system architecture with multi-relay coils can extend the transfer distance, and simultaneously maintain the stable transfer efficiency. The system architectures with multi-transmitter and multi-receiver coils can reduce the sensitivity of system transfer characteristics to the horizontal and vertical misalignment. Summarily, this section mainly demonstrates the system architectures with three or four coils, multi-relay coils, multi-transmitter and multi-receiver coils.

3.1.1. System Architectures with Three and Four Coils

Hamam *et al.* [13] proposed a kind of system architecture with three coils based on CMT, and further pointed out that the fundamental principle underlying this power transfer scheme is analogous to the electromagnetically induced transparency (EIT) process. Kiani *et al.* [25] presented the equivalent circuit model of system architecture with three coils based on CT, and pointed out that the drawback of system architectures with four coils is the low transfer power despite the high transfer efficiency. By contrast, the system architecture with three coils can improve the transfer power, and simultaneously keep the transfer efficiency invariable. However, an assumption had been made that the mutual inductance M_{23} and M_{34} could be adjusted simultaneously in Figure 3a, thus two degrees of freedom can be used to optimize the transfer efficiency .

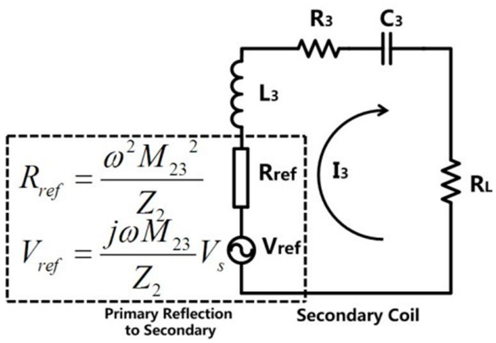
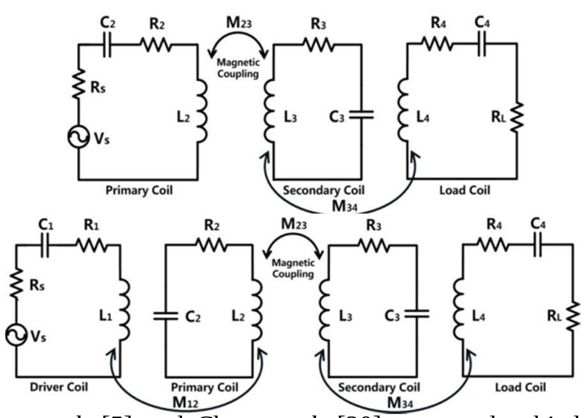


Figure 3. ***(a)*** *Equivalent circuit model of system architecture with three coils;* ***(b)*** *equivalent circuit model of system architecture with four coils. The cross-coupling effects between non-adjacent coils are neglected in Figure 3a,b for simplicity.*



Kurs *et al.* [5] and Chen *et al.* [20] presented a kind of four coils system architecture without resonant capacitors in the driver coil and load coil, just like the one in Figure 3b without C1 and C4. Additionally, Chen *et al.* [20] pointed out that the driver coil and load coil can be used to realize impedance matching functions. The other system architectures with four coils [19,26,27,30,37] can be all denoted by the equivalent circuit model in Figure 3b.

Actually, system architectures should be properly selected on the basic of practical requirements, such as transfer distance, transfer efficiency, load power rating and so on. Compared with the system architecture with two coils, those with three or four coils have one or two adjustable freedom degrees. In order to match the reflected impedances and further optimize the transfer efficiency and transfer power, M_{34} in the system architecture with three coils and M_{12}, M_{34} in the system architecture with four coils in Figure 3 can be adjusted although M_{23} is fixed. Suppose that the quality factors of resonant coils are extremely high, then the internal parasitic resistances can be ignored, consequently, the reflected impedances in Figure 3a,b can be written as:

$$R_{ref\,3\to2} = \left(\frac{M_{23}}{M_{34}}\right)^2 R_L \qquad (14)$$

$$R_{ref\,2\to1} = \omega^2 \left(\frac{k_{12}k_{34}}{k_{23}}\right)^2 \frac{L_1 L_4}{R_L} \qquad (15)$$

Where $R_{ref\ 3\to2}$ ($R_{ref\ 2\to1}$) represents the reflected impedance from the secondary (primary)coil to the primary (driver) coil.

3.1.2. System Architectures with Multi-Relay Coils

It is significant to research the system architecture with multi-relay coils, because it can extend the transfer distance with unchangeable efficiency. Zhang *et al.* [15] and Kim *et al.* [16] analyzed the transfer characteristics of system architecture with multi-relay coils based on CMT. Kim *et al.* [16] pointed out that either a coaxially arranged relay coil or a perpendicularly arranged relay coil can improve the system transfer efficiency considerably. Zhong *et al.* [21–23] analyzed the transfer characteristics of system architecture with multi-relay coils based on CT, which is arranged coaxially, non-coaxially and circularly, as shown in Figure 4. In the coaxial arrangement, the cross-coupling effects of nonadjacent relay coils are taken into the consideration. The operating frequency, the spacing of relay coils and the load values should be adjusted properly with the purpose of maximizing transfer efficiency. In the circular arrangement, there are two opposite power flow paths. The interactions between these two paths are analyzed with superposition principles and explained with the help of vector diagrams. Under resonant frequency operation, the in-phase superposition reinforcement and out-phase superposition diminution phenomena of the current amplitude could occur in some relay coils of the system with even number of relay coils. But such phenomenon does not occur in the system with odd number of relays coils at resonant frequency. Additionally, the cross-coupling effects may have some effects on this phenomenon, especially when the non-adjacent coils are close enough. This unwished superposition phenomenon can be diminished by adjusting the operating frequency properly.

Ahn *et al.* [28] studied the frequency splitting phenomenon both for even and odd numbers of relay coils, and further pointed out that there was no splitting frequency point which coincided with original resonant frequency in the case of even number of relay coils, but there was in t he case of odd number of relay coils. Moreover, some guidelines were also given to determine how to select the optimum locations and numbers of relay coils. Stevens [38] proposed the Magneto-Inductive Power Surface (MIP surface) which can transfer power and data wirelessly. Actually, a MIP surface is a kind of metamaterial structure which is often composed of arrays of identical coupled resonant electrical circuits. He also concluded that high resonant frequency is beneficial for system transfer characteristics. Puccetti *et al.* [36] proposed a novel array of coplanar resonators, which included six identical SRs, and also explained its corresponding transfer characteristics. Wang *et al.* [42] studied similar multi-relay coils system architecture in Figure 5a, which aims to power mobile objects, and Figure 5b shows its magnetic field distribution. A novel explanation of the non-uniform magnetic field distribution along the array is presented, that is, the coupled mode of the relay coils system forms a standing wave on the array, with the phase difference between neighboring resonators depending on the operating frequency.

Figure 4. *System architecture with multi-relay coils. The left one shows the system architecture with multi-relay coils which is arranged non-coaxially. The right one shows the system architecture with multi-relay coils which is arranged circularly.*

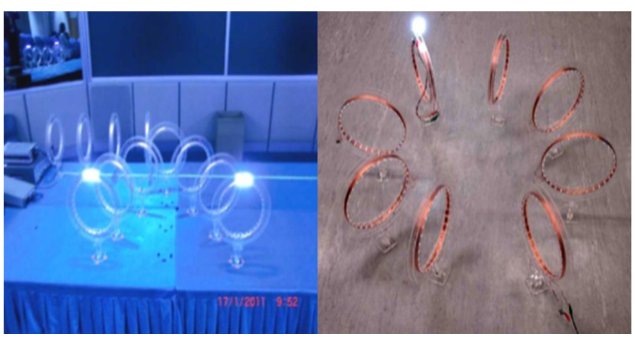
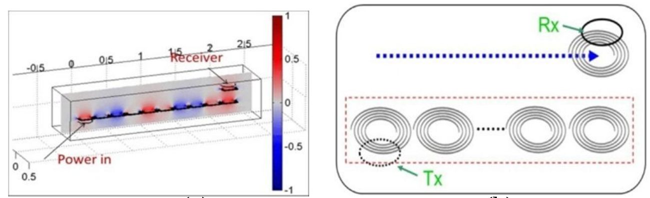


Figure 5. (a) *System architecture with multi-relay coils. One resonant coil acts as the transmitter and one resonant coil acts as the receiver. This system can be used to extend transfer distance or power mobile objects;* ***(b)*** *Magnetic field distribution of system architecture with multi-relay coils. The two marked coils act as the transmitter and the receiver, the color strength shows the distribution situation of magnetic field.*



(a) (b)

System architectures with multi-relay coils are actually the extension of those with two coils, but more complicated. For instance, the analysis processes of reflected impedances are more complex, and the effects on transfer characteristics caused by the cross-coupling of nonadjacent relay coils can't be ignorable. Fortunately, the bidirectional reflectance impedance analysis (BRIA) method is still applicable. The theoretical and quantitative analysis of the optimal operating frequency and relative distance are hot spots, because the system parameters in different applications need to be reanalyzed and redesigned. Furthermore, it should be noted that increasing the numbers of relay coils would introduce additional energy losses due to their limited quality factors.

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3.1.3.System Architecture with Multi-Transmitter and Multi-Receiver Coils

The transfer characteristics of system architectures with multi-receiver coils are analyzed based on both CMT [14,17] and CT [24]. Kurs *et al.* [14] mentioned that increasing the number of the receiver coils can improve the overall efficiency of power transfer, even if the efficiency of the transfer to each individual receiver coil is relatively low. Kim *et al.* [17] further pointed out that the overall efficiency tended to be saturated, even when the number of receiver coils was increased, so the number of receiver coils should be chosen carefully. Cannon *et al.* [24] proposed an equivalent circuit model of the system architecture with multi-relay coils, and pointed out that the frequency splitting phenomenon will happen when two receiver coils are placed close enough.

The transfer characteristics of system architectures with multi-transmitter coils are analyzed based on CT in [29,31–33]. Oodachi *et al.* [29] proposed the transmitter coil array which has in-phase and out-phase excitation modes. Selecting the appropriate excitation mode can improve the transfer efficiency according to the position of the receiver coil. Casanova *et al.* [31] found that the interactions between receiver coils can be reduced in the system architecture with multi-transmitter coils; this is mainly because the reflected impedances in the voltage source side are converted from series to parallel. Ahn *et al.* [33] investigated the operation of system architectures with multi-transmitter or multi-receiver coils. In accordance with their cross-couplings, he proposed a frequency adjusting method to maximize the transfer efficiency and transfer power, and also to realize soft switching simultaneously.

Huge development space and bright prospects exist in system architectures with multi-transmitter and multi-receiver coils, especially in the low or medium power applications such as medical implantation and consumer electronics. Some researchers have already considered the cross-coupling effects on transfer characteristics, but usually limited to no more than three resonant coils. Once the number of transmitter and receiver coils increases, or the receiver coils move horizontally and vertically, the analysis processes will become more complicated. Hence, in order to satisfy the requirements in the practical applications, some important problems, including the cross-coupling effects, the selection of the coil number and geometrical shapes of the transmitter and receiver coils, the horizontal and vertical motion of the receiver coils and the design of control strategies, should be carefully considered.

3.2 Frequency Splitting Phenomenon and Impedance Matching

Frequency splitting phenomenon happens in the over coupled area, which affects system transfer characteristics. Besides, impedance matching is a kernel problem in HRC. The studies, including system architectures, transfer characteristics and frequency splitting, are all focused on impedance matching. The reflected impedances, the parasitic resistances of the coils, the internal resistance of the source and the load impedance constitute an intricate impedance network, which decide the system transfer characteristics simultaneously.

3.2.1.Frequency Splitting Phenomenon

Sample *et al.* [26] classified system working areas into over coupled area, critically coupled point and under coupled area, as shown in Figure 6. He further pointed out that there are two operating frequency modes in the system architecture with two coils. In the lower frequency mode, the current in the transmitter coil is in phase with that in the receiver coil, but they are anti-phase in the higher frequency mode. Similar conclusions are also mentioned in [48,49].

Substantially, frequency splitting is not an intrinsic property of HRC, but the result of pursuing high power transfer. Analogous curves can be also acquired by simulating the equivalent circuit model in Figure 1a, and the coupling coefficient and driving frequency should be swept simultaneously. Critically coupled points only exist in a resonant state, which indicates that the reflected impedance from the secondary coil to the primary coil is identical to the initial impedance of the primary coil.

In this situation, impedance matching condition is satisfied, so the transfer power arrives at the maximum value, but the transfer efficiency is merely 50%. In the under coupled area, the reflected impedance from the secondary coil to the primary coil is less than the initial impedance of the primary coil because of the reduced coupling coefficient, so both the transfer efficiency and transfer power will decrease. In the over coupled area, the reflected impedance from the secondary coil to the primary coil is higher than the initial impedance of the primary coil because of the increasing coupling coefficient, this leads to higher transfer efficiency, but lower transfer power. In order to enhance transfer power in over coupled area, the driving frequency should be adjusted away from system resonant frequency to track the frequency splitting points, which can realize impedance rematch. Additionally, it is worth noting that the equality of transfer power at critically coupled point and frequency splitting point is tenable only when the total resistance in the primary coil is identical to those in the secondary coil. Although imaginary power will emerge when the system driving frequency shifts away from the resonant frequency, the bifurcation phenomenon based on maximizing transfer efficiency will not happen in the architecture shown in Figure 1a, and the conception of power factor mentioned in Section 3.2 should be introduced to evaluate this imaginary power. The frequency splitting phenomenon will happen in the system architecture with multi-relay, multi-transmitter and multi-receiver coils if adjacent two or more resonant coils are in close enough proximity that their magnetic fields are relatively strongly coupled [24]. So many resonant coils will form a complicated frequency splitting situation which is worthwhile to be further studied.

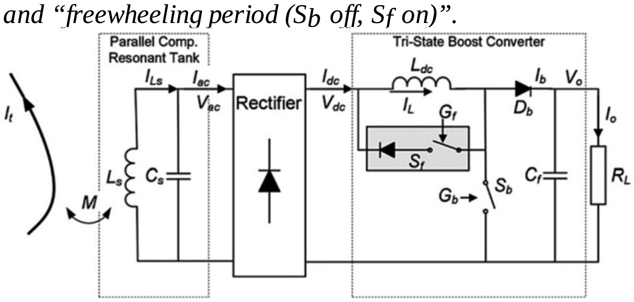
3.2.2. Impedance Matching

In order to realize impedance matching, tracked the splitting frequency points in the odd or even mode, but this method is only applicable in the over coupled area. Chen *et al.* [20] proposed an impedance matching method by adjusting the relative distances or angles between adjacent coils. This method is difficult to realize in practice, because it needs complicated control systems as well as accurate actuators. An anti-parallel resonant structure formed by the forward and reverse driver coils, which can prevent the coupling coefficient from dramatic distance-related changes. By doing this, the transfer efficiency can be stabilized despite the changing distance. However, this method discards the high transfer efficiency and transfer power characteristics in the close range simultaneously. By using the additional circuits containing inductive and capacitive components, maintained the system resonant frequency to be 13.56 MHz within the Industrial Scientific Medical (ISM) band, and one matching algorithm based on improving the transfer efficiency was presented. However, its matching effects are not smooth due to the use of discrete switch block. The volumes, weights and costs of these reactive components should be also considered. A DC-DC converter to execute impedance matching by adjusting the duty ratio.

$$\frac{V_{in}}{V_{out}} = \frac{(1-D)}{D}, \; V_{in}I_{in} = V_{out}I_{out}, \; V_{out} = I_{out}R_L \quad (16)$$

$$\frac{V_{in}}{I_{in}} = \frac{R_L(1-D)^2}{D^2} \quad (17)$$

Figure 7. *A novel parallel compensated receiver with tri-state boost converter. The three operating modes are "boost (S_b on, S_f off)", "power delivery (S_b off, S_f off)" and "freewheeling period (S_b off, S_f on)".*



Among the methods discussed above, DC/DC matching appears to be most promising, because it can realize not only impedance matching but also power conversion. Multiple matching by merging the respective advantages of aforementioned methods is also a preferable solution, but the corresponding control strategy should be carefully designed. To better realize impedance matching, the problems of load detection, mutual inductance calculation and parameter measurement are extremely important. An effective transient load detection method, but it is only suitable for pure resistance detection, unfortunately, reactive loads are ubiquitous in the practical applications. A compact model of mutual inductance at various axial and lateral displacements, and he found that the mutual inductance value relied on operating frequency, but this phenomenon only happens near the self-resonant frequency of the coil. However, this calculation process is still complex, and is sensitive to many other parameters in the practical online applications. A new idea for measuring the transfer distance and orientation by using magnetoquasistatic fields. Solving the problems, including load detection, mutual inductance calculation and parameters measurement, are prerequisites for realizing impedance matching, and they are also technological difficulties.

3.3. Optimization Design Flow

A global optimization design flow based on improving the transfer efficiency. In order to achieve this goal, the driving frequency and resonant frequency must all coincide with the frequency where the quality factor of the coil is maximized, and he further pointed out that the maximum quality factor will be achieved when the ratio between the radius of the coil and the cross-sectional radius of the conductor is roughly 9.5. A design algorithm to determine the optimal resonant frequency and relevant transfer efficiency for system architecture with two coils, and a trade-off between low resonant frequency and high transfer efficiency should be decided first. The operating frequency increased endlessly until the transfer power was just lower than the rated power with the purpose of improving transfer efficiency, which was actually the tradeoff between transfer efficiency and transfer power. Similarly, An iterative design methodology which can optimize geometry parameters to improve transfer efficiency. And they further presented a new figure of merit (FoM), which was substantially a trade-off evaluation criterion between power transfer efficiency (PTE) and power delivered to the load (PDL). Based on the proposed FoM, relevant iterative design procedures for system architectures with two, three and four coils were also demonstrated. They drew the conclusion that system architecture with two coils was suitable for strongly coupled coils used in applications that need large PDL, while a system architecture with three coils was suitable for loosely coupled coils where the coupling distance varies considerably, and system architecture with four coils was optional when small PDL is required at high PTE and the coils are loosely coupled but have a stable coupling distance and alignment.

From the aforementioned analysis, we can draw the conclusion that optimization design flows are actually the trade-off processes which should be decided according to predesign objectives and corresponding boundary limitations. It is suggested that the transfer efficiency should be considered preferentially, because the transfer power can be improved through increasing the output power of the driver source. It is also worth noting that the transfer efficiency of system architectures with three or four coils is multiplied by the local transfer efficiency between adjacent resonant coils, so in order to optimize global transfer efficiency, the local transfer efficiency must be optimized primarily.

3.4. Applications

HRC is widely applied because of its mid-range, non-radiative and high-efficiency merits. In medical implantation applications, batteries are necessary because the micro-system implanted in an organism needs to be powered. However, battery charging or replacements will cause the additional economic burden and physical pains on patients. Fortunately, HRC is appropriate to solve this tough problem. A wireless energy transfer system which is designed and implemented for the power supply of micro-implantable medical sensors, and the volume of the whole implanted part is really small. It pointed out that batteries can be replaced by this novel technology, the energy for implantable devices can be supplied wirelessly. A new wireless power mat system which can supply the energy for medical implants in the body of free-moving laboratory animals.

In the industrial and consumer electronics applications, HRC is of great value to industrial robots, intelligent home appliances, personal digital assistants and so on, which all need convenient charging technologies. Kuipers *et al.* pointed out that HRC can be used in underwater detection and illumination. Kim *et al.* designed a suit of power supply system for LED TV, the operating frequency, transfer efficiency and transfer power are 250 kHz, 80% and 150 W, respectively. Xie *et al.* mentioned that HRC can overcome the bottleneck of wireless sensor network caused by the limited battery energy, which will make wireless senor network immortal.

In transportation applications, wired charging for power batteries may be dangerous and inconvenient, fortunately, this charging process can be simplified by WPT. Except for this stationary charging, dynamic charging (or called roadway-charging) is attracting more and more attention. This concept was first proposed in the early 70s [93]. Recently, the Korea Advanced Institute of Science and Technology (KAIST) developed the Online Electric Vehicle (OLEV) platform, which has already been used in Seoul Grand Park. OLEV is a really meaningful achievement, which can increase all-electric-range (AER) and lower the battery cost. Maybe, it can promote a revolutionary progress of electric vehicle industry. The commercialization processes of this charging technology have been started in many countries, such as Korea, USA, UK and Germany. In summary, wireless power charging for electric vehicles is a promising technology, which is also supported by many companies including Volvo, Citroen, Evatran, Witricity, Halo IPT, *etc*.

IV. Conclusion

This paper has reviewed wireless power transfer via HRC, and mainly included the principle elaboration, hot spot analysis and future tendency prediction. High operating frequencies and high quality factors are the basic reasons why HRC can transfer power with high efficiency over long distances. The additional adjusting freedoms existing in different system architectures are beneficial for optimizing system transfer characteristics. The global optimization design and control methods by considering multi-effects factors are also valuable for its engineering applications. The basic principles of HRC and IPT are identical, despite some distinctions between them, so mutual learning and assimilation between HRC and IPT are beneficial for both fields. In practice, a certain rated power is required, but this MHz resonant frequency may bring a great challenge to some electronic components, for example, the rectifier, MOSFET driver and so on. Fortunately, the modern semiconductor and materials industry are developing rapidly. HRC actually belongs to a marginal discipline between physics and electronics, so it needs the efforts from different research fields. We wish it a bright future.

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