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Review

A Critical Review of Wireless Power Transfer via Strongly Coupled Magnetic Resonances

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Abstract: Strongly coupled magnetic resonance (SCMR), proposed by researchers at MIT in 2007, attracted the world's attention by virtue of its mid-range, non-radiative and high-efficiency power transfer. In this paper, current developments and research progress in the SCMR area are presented. Advantages of SCMR are analyzed by comparing it with the other wireless power transfer (WPT) technologies, and different analytic principles of SCMR 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 SCMR are discussed.

Keywords: wireless power transfer; strongly coupled magnetic resonances; mid-range non-radiative high-efficient power transfer

1. Introduction

Wireless power transfer is not strange to human beings, since as early as 1889 Nikola Tesla had invented the famous Tesla coils which can transfer power wirelessly. Thereafter, researches on wireless power transfer began [1]. In 1964, William C. Brown proposed a point-to-point wireless power transfer scheme on the basic of microwave beams [2]. In 1968, American engineer Peter Glaser presented a concept of a space solar power station, and further conceived that solar energy could be converted into electric energy first, and then transmitted to the Earth in the form of microwaves [3]. Tremendous progress took place in the solar power satellite (SPS) project during the 1970s [4], which indicated that human beings had grasped this spatial electric energy transfer technology. In 2007, wireless power transfer shocked the world again, the research team headed by Professor Marin Soljacic of MIT proposed strongly coupled magnetic resonance (SCMR), 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 demosntrated 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. Hence, wireless power transfer based on electromagnetic radiation mode is not appropriate for the civilian use. The principle of electric field coupling mode is essentially the redistribution of the surface charges on the object. 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. According to the transfer distance, the magnetic field coupling mode can be mainly classified into short-range electromagnetic induction and mid-range SCMR. The transfer efficiency and transfer power of electromagnetic induction are normally high, but the transfer distance is limited to centimeter level. In contrast, the transfer efficiency and transfer power of SCMR are a little lower, but the transfer distance can achieve meter level to realize mid-range power transfer. 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, SCMR fills exactly the void in the mid-range wireless power transfer applications.

Recently, some colleges and research institutes have already achieved many meaningful results in terms of SCMR, which mainly included the topics of principle elaboration, transfer characteristics, new materials, interference and practical applications [8]. Normally, either coupled mode theory (CMT) [9–17] or circuit theory (CT) [18–35] can be used for analyzing SCMR. Transient analysis based on CT is sometimes more accurate than that based on CMT [18], thus CT is widely adopted. Various hot research spots, including system architectures [14–17,19–47], frequency splitting [11,24,26,28,48,49], impedance matching methods [20,26,27,50–60], optimization designs [25,42,61–77] and practical applications [37,78–83] have been actively investigated.

SCMR is still under development, so naturally, there are many urgent issues which should be settled. The aforementioned works analyze different problems and further put forward relevant solutions based on their research emphasis. However, many research spots in this field are quite different, and corresponding results may not be identical despite describing the same research spot. In order to facilitate the following researchers' work, it is very significant to review the existing research results. Compared with [8], this paper emphatically elaborates similarities and differences between CMT and CT, and further points out the distinctions between SCMR and inductive power transfer (IPT). The hot research spots, including system architectures, frequency splitting phenomenon, impedance matching methods, optimization designs and practical applications are summarized, and relevant technical difficulties are pointed out simultaneously. Finally, future trends in this field are forecast.

2. 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 [84]. According to CMT, the physical processes of power transferring from one resonant object to another can be described as:

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

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, 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:

$$\begin{cases} \dfrac{da_m(t)}{dt} = (i\omega_m - \Gamma_m)a_m(t) + iK_{mn}a_n(t) + F_m(t) \\ \dfrac{da_n(t)}{dt} = (i\omega_n - \Gamma_n - \Gamma_L)a_n(t) + iK_{nm}a_m(t) \end{cases} \tag{2}$$

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:

$$\begin{cases} a_m(t) = \dfrac{\left[(\Gamma_n + \Gamma_L) + i(\omega - \omega_r)\right]Ve^{i\omega t}}{K^2 + (j\omega - j\omega_r + \Gamma_m)(j\omega - j\omega_r + \Gamma_n + \Gamma_L)} \\ a_n(t) = \dfrac{iKVe^{i\omega t}}{K^2 + (j\omega - j\omega_r + \Gamma_m)(j\omega - j\omega_r + \Gamma_n + \Gamma_L)} \end{cases} \tag{3}$$

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

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

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

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:

$$\Gamma_{L\eta_{\max}} = \Gamma_n\sqrt{1+\frac{K^2}{\Gamma_m\Gamma_n}},\ \Gamma_{LP_{L\max}} = \frac{K^2+\Gamma_m\Gamma_n}{\Gamma_m},\ K_{P_{L\max}} = \sqrt{\Gamma_m\Gamma_n+\Gamma_m\Gamma_L} \quad (8)$$

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]:

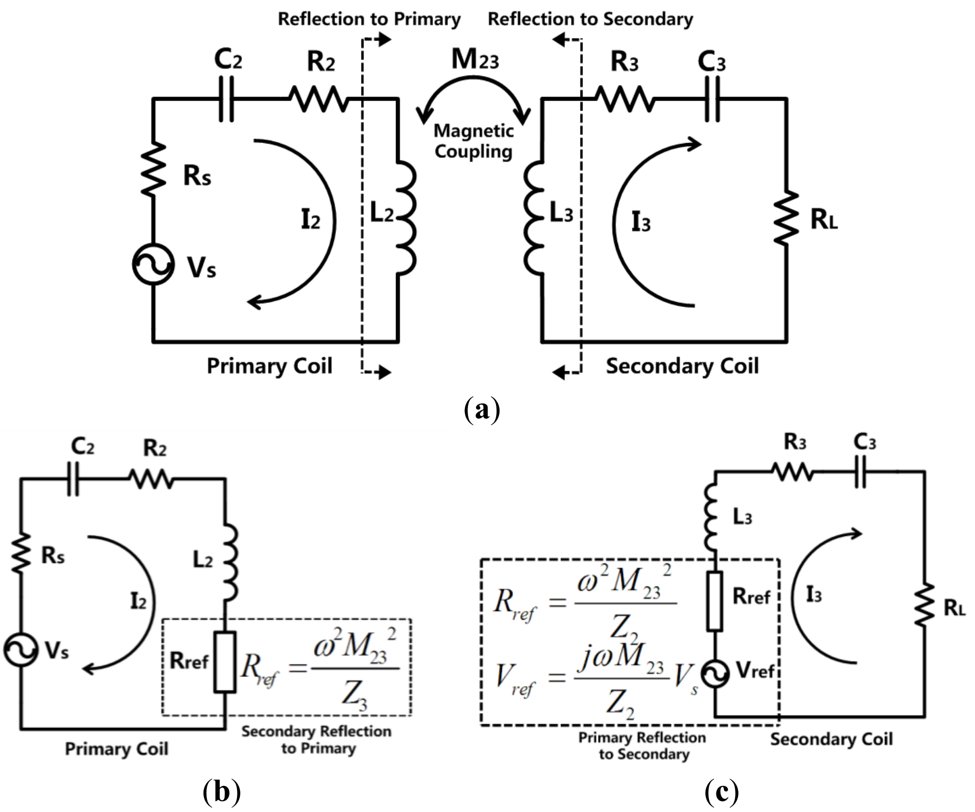
$$\omega = \omega_r,\ \omega_r \pm [K^2 - 0.5\Gamma_m{}^2 - 0.5(\Gamma_n+\Gamma_L)^2]^{0.5} \quad (9)$$

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.

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]:

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

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

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

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:

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

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.

2.3. Comparative Analysis between Coupled Mode Theory and Circuit Theory

Both CMT and CT can be used to analyze SCMR, but they belong to different science branches, so it is meaningful to clearly distinguish them. According to CMT, we have [5,84]:

$$\Gamma_L = \frac{R_L}{2L_3},\ \Gamma_3 = \frac{R_3}{2L_3},\ \Gamma_2 = \frac{R_2}{2L_2},\ K = \frac{\omega}{2}k = \frac{\omega M_{23}}{2\sqrt{L_2 L_3}} \tag{14}$$

The new parameter k here corresponds to the coupling coefficient in CT, and the subscripts 2 and 3 are corresponding to the subscripts m and n in Section 2.1, respectively. Assume that the system works in the resonant state and the internal resistance of the voltage source is ignored, then substitute Equation (14) into Equation (8) and further simplify the expressions, we can draw that Equations (8) and (13) are absolutely identical, this verifies that the aforementioned analysis based on CMT and CT are equivalent in the resonant state.

If the system works in the non-resonant state, the frequency splitting phenomenon based on maximizing the transfer power appears, and this critical condition in CMT can be derived as:

$$K^2 = 0.5{\Gamma_2}^2 + 0.5(\Gamma_3 + \Gamma_L)^2 \tag{15}$$

By substituting Equation (14) into Equation (15), its counterpart in CT can be rewritten as:

$$k^2 = \frac{1}{2}[(\frac{R_2}{\omega L_2})^2 + (\frac{R_3 + R_L}{\omega L_3})^2] \tag{16}$$

Suppose that the total resistance and self-inductance of the two resonant coils are identical, then Equation (16) can be further simplified into the critical condition in CT where the frequency splitting phenomenon based on maximizing transfer power also appears. This verifies that CMT and CT are the same for analyzing the transfer power characteristics in the non-resonant state.

The comparative study in this section is based on the steady state analysis, but the transient characteristics analyzed with CMT and CT are different. To go much further, CMT is only applicable to the coils with high quality factor and large coupling distance, but it simplifies the analysis by reducing the order of the differential equations by half compared to CT [18].

2.4. Distinctions between Strongly Coupled Magnetic Resonances and Inductive Power Transfer

Up to now, inductive power transfer (IPT) has already been developed for about twenty years, and there have been many achievements, especially in the field of electric vehicle charging applications [63,72,73,85,86]. Historical backgrounds, technological issues, and engineering applications of IPT over the past two decades are fully summarized in [87]. Compared with IPT, SCMR is still under development. In order to deeply understand the two aforementioned technologies, summarizing their differences is meaningful. It should be noted that they all conform to Faraday's and Ampere's law. So the differences primarily include design approaches, system architectures, parameter selection and transfer characteristics.

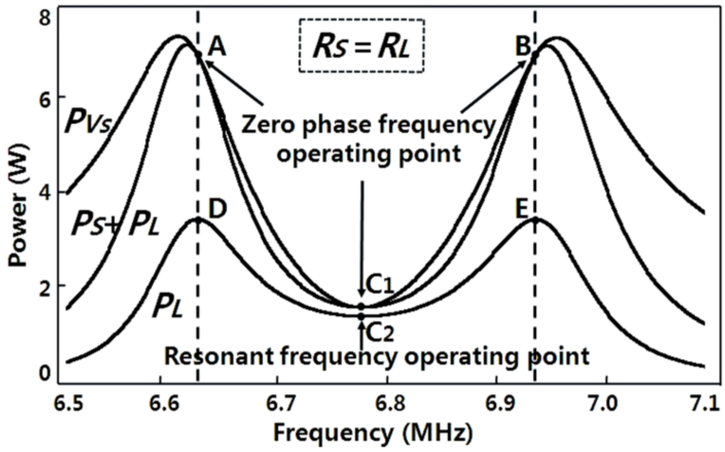
(1) Diverse system architectures are utilized in SCMR, which can facilitate the impedance matching to optimize the system transfer characteristics. The parasitic capacitance of the coil is ordinarily utilized to produce a really high resonant frequency. By contrast, the system architecture with two coils is generally adopted in IPT, and the basic topologies include series-series, series-parallel, parallel-series and parallel-parallel. The secondary coil in IPT should be tuned at the operating frequency to enhance the power transfer. In order to eliminate the imaginary power in some topologies, the lumped capacitance of the primary coil should be deliberately designed to compensate both the primary self-inductance and the reflected impedance. Except for the series-series topology, the compensation capacitance of the primary coil in the other three topologies are all affected by either mutual inductance values or load impedances [85];

(2) Because parasitic capacitances are usually adopted for tuning, the operating frequency of SCMR is roughly in the MHz range. Consequently, the quality factors are very high. When the transfer distance increases, these high quality factors can alleviate the sharp decline in the transfer efficiency which is caused by the reduced coupling coefficient, so the high transfer efficiency in meter scope can be realized. Compared with SCMR, the operating frequency of IPT is ordinarily in the KHz range, and ferromagnetic materials are usually used for improving the coupling, and, hence, power transfer. The quality factors of IPT are normally designed below 10 [85,88], because the transfer power will drop precipitously for larger quality factor values [60]. Without the compensation of high quality factors, the transfer efficiency of IPT naturally declines sharply with the increasing transfer distance, so the effective transfer distance is usually within 20 cm, but the transfer power can reach kilowatts level;

(3) The frequency splitting phenomenon exists in both SCMR and IPT, but with different objectives. The former aims to maximize the transfer power, and the latter one aims to achieve a unity power factor [85]. According to the circuit model depicted in Figure 1a, the AC sweep analysis results by executing Spice simulations are showed in Figure 2. P_{VS}, Ps and P_L represent the output power of the AC voltage source, the dissipation power of the source internal resistance and the load resistance. A and B represent the frequency splitting points based on

achieving the unity power factor, D and E represent the frequency splitting points based on maximizing the transfer power, C_1 and C_2 are at the resonant frequency point. Obviously, the frequency splitting phenomenon appears in Figure 2, and A and D (or B and E) overlap with each other. But it should be noted that the premise is the equivalence between R_S and R_L, once this assumption is not satisfied, the misalignment between A and D (or B and E) will happen.

Figure 2. Frequency splitting phenomenon in SCMR and IPT.



3. Classification and Elaboration of Hot Research Spots

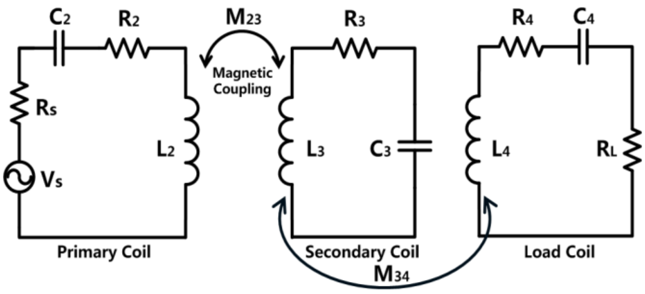
3.1. System Architectures

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.

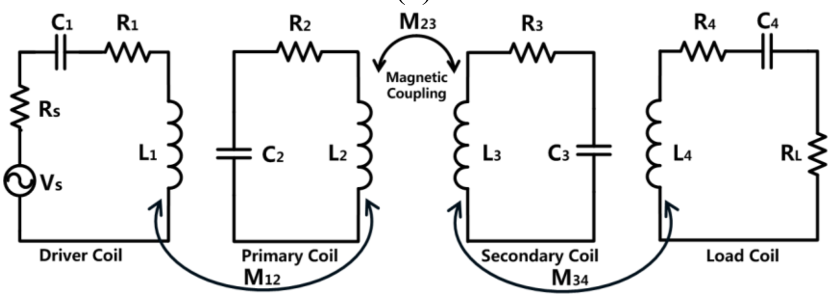
3.1.1. System Architectures with Three and Four Coils

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 and transfer power.

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.



(**a**)



(**b**)

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:

$$R_{ref\,3\to2} = (\frac{M_{23}}{M_{34}})^2 R_L \tag{17}$$

$$R_{ref\,2\to1} = \omega^2 (\frac{k_{12}k_{34}}{k_{23}})^2 \frac{L_1 L_4}{R_L} \tag{18}$$

where, $R_{ref\,3\to2}$ ($R_{ref\,2\to1}$) represents the reflected impedance from the secondary (primary) coil to the primary(driver) coil. Equations (17) and (18) show that a tight coupling can be realized by adjusting the corresponding mutual inductances or coupling coefficients between adjacent coils, then the transfer characteristics can be optimized. In practice, the parasitic resistances of resonant coils cannot be ignored due to the limitations of wire materials, especially when the skin and proximity effects are considered, and these will make the aforementioned analysis a little more intricate. Although the system architectures with three or four coils can be utilized in the occasion of variation transfer distances or load conditions, it is difficult to adjust the relative distances and angles between adjacent coils automatically, and additional actuators may increase the costs. Determining how to make the resonant frequency of different coils be the same and how to keep the system always in the resonant state and further in the best work state are the technological difficulties. Moreover, the effects on system resonant frequency caused by cascaded rectifiers and capacitors need to be further studied.

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 the 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.

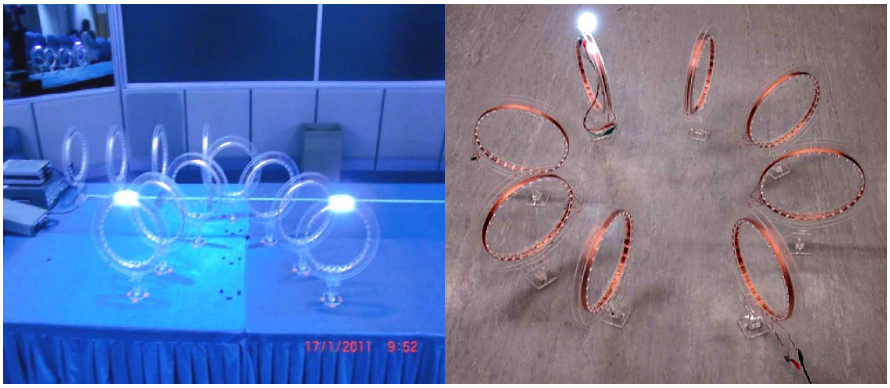
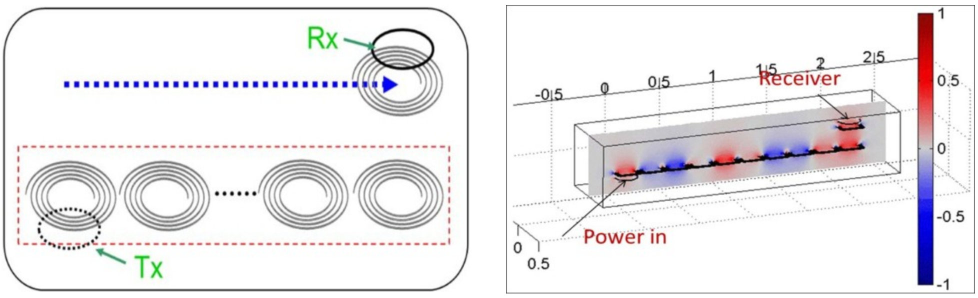


Figure 5. (**a**) System architecture with multi-relay coils. One resonant coil acts as the transmitter and one resonant coil acts as the receiver. This system can be used to extend transfer distance or power mobile objects; (**b**) Magnetic field distribution of system architecture with multi-relay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

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.

3.1.4. Metamaterial-Based System Architecture

Recently, metamaterials have found applications in many fields, such as energy harvesting [39], magnetic resonance imaging [40], data transfer [41] and wireless power transfer [42]. But this paper only focuses on wireless power transfer with metamaterials.

As we know, metamaterials are not a new kind of material, but rather an artificial arrangement of identical unit cells. Most of them are composed of arrays of identical coupled resonant electrical circuits—often in the form of magnetically coupled LRC resonators [38], so metamaterials can be designed carefully to possess some peculiar electromagnetic properties not seen in natural materials, such as a negative-refractive index and evanescent wave amplification. Further, these two merits enable metamaterials have the ability to control the surrounding magnetic field distribution. Quality factors and mutual coupling strength actually determine system transfer characteristics. Naturally, metamaterials can be introduced to improve the mutual coupling strength, and, hence, power transfer efficiency [43]. Generally, the negative-refractive index character requires both effective permittivity and permeability to be negative. However, in the deep subwavelength limit, the magnetic field and electric field decouple, and only one of them is required to be negative [44]. Fortunately, many SCMR systems fall in the deep subwavelength limit, because their sizes are much smaller than the working wavelength [45]. As an extension study, the theoretical analysis and numerical modeling on metamaterials to improve the power transfer efficiency are conducted by Yaroslav [46] and Huang [47]. The applications of metamaterials in SCMR is a promising research direction, but the energy losses, the volume sizes, the fabrication and the cost of metamaterials should be carefully considered.

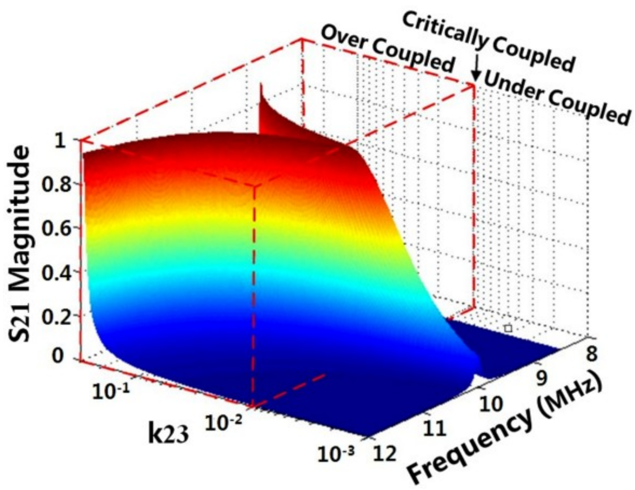
3.2. Frequency Splitting Phenomenon and Impedance Matching

Frequency splitting phenomenon happens in the over coupled area, which affects system transfer characteristics. Besides, impedance matching is a kernel problem in SCMR. 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].

Figure 6. S_{21} magnitude as a function of frequency and coupling coefficient k_{23}. The part in the red hexahedron is called over coupled area, the remaining part is called under coupled area, and the connection between them is critically coupled point.



Substantially, frequency splitting is not an intrinsic property of SCMR, 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

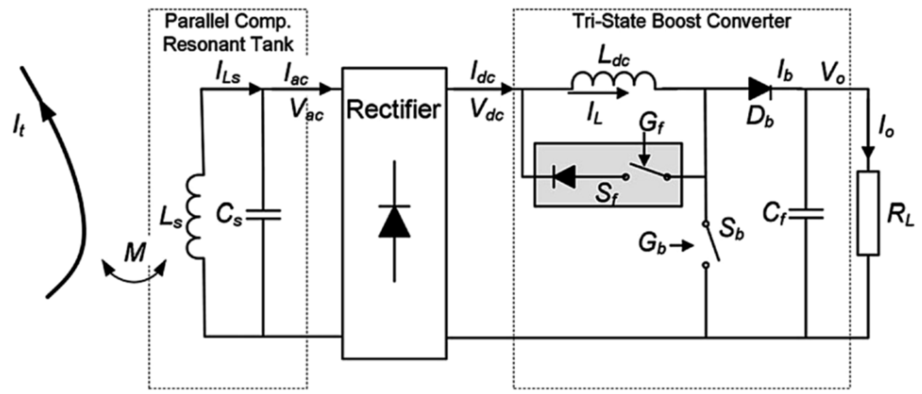
In order to realize impedance matching, Fu *et al.* [51] tracked the splitting frequency points in the odd or even mode, but this method is only applicable in the over coupled area. Chen *et al.* [20] and Duong *et al.* [54] proposed an impedance matching method by adjusting the relative distances or angles between adjacent coils. This method is difficult to realize in practice, because it needs complicated control systems as well as accurate actuators. Lee *et al.* [53] proposed 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, Beh *et al.* [56] 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. Moriwaki *et al.* [57] adopted a DC-DC converter to execute impedance matching by adjusting the duty ratio. For example, if the buck-boost topology is used, equivalent impedances can be adjusted from zero to infinity, Equations (19) and (20) show this derivation process:

$$\frac{V_{in}}{V_{out}} = \frac{(1-D)}{D}, \; V_{in}I_{in} = V_{out}I_{out}, \; V_{out} = I_{out}R_L \tag{19}$$

$$\frac{V_{in}}{I_{in}} = \frac{R_L(1-D)^2}{D^2} \tag{20}$$

Pantic *et al.* [60] proposed a novel parallel compensated receiver with tri-state boost converter. By adjusting the additional degree of freedom (the switch in Figure 7), the discontinuous current drawn by the tri-state boost converter can be profiled to inject an appropriate reactance into the resonant tank to tune the system and further achieve optimal power transfer. This new idea is valuable for the developments of impedance matching methods, and the application problems of SCMR in different occasions may be solved by introducing analogous one or more adjusting freedoms and corresponding control strategy. Moreover, Sample *et al.* [59] comprehensively evaluated the main kinds of impedance matching methods used to adapt to variations in range, orientation and load, and presented a full end-to-end system capable of adapting to real-time changes in the environment while maintaining optimum efficiency.

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. Wang *et al.* [89] proposed an effective transient load detection method, but it is only suitable for pure resistance detection, unfortunately, reactive loads are ubiquitous in the practical applications. Raju *et al.* [90] proposed 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. Arumugam *et al.* [91] proposed 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

3.3.1. Optimization Design of Circuit Topology, Physical Structure and High Quality Factor

It is worth noting that the fundamental topologies are only series-series, series-parallel, parallel-series and parallel-parallel virtually, the other novel topologies are all derived from them. Chen *et al.* [62] studied series-parallel mixed-resonant coupling topology, and pointed out that this topology was virtually a synthesis of series and parallel topologies, and it has superior advantages that the transfer distance is longer than series topology and the transfer efficiency is higher than parallel topology. Villa *et al.* [63] proposed a series-parallel-series (SPS) topology which can transfer rated power even with high misalignment. Lee *et al.* [64] concluded that high frequency (within megahertz) loss is mainly caused by the skin effect and proximity effect, and further proposed a surface spiral layout with hollow cross section. In order to decrease the skin-effect loss, the wall thickness of the coil is identical to the skin depth. Three turns occupy 120 degrees in a spiral pattern on a surface relatively, which consist of the whole hollow coil. The proximity effect is restrained by this spatial arrangement, this is because the magnetic fields of the outside of the circular cross section are connected smoothly without adding or subtracting the fields. Kim *et al.* [65] improved transfer efficiency with the use of high-temperature superconducting (HTS) receiver coil. Budhia *et al.* [66] emphatically studied the design and optimization of circular magnetic structures, as well as its influence factors like transfer distance, horizontal misalignment, durability, weight, cost efficiency and so on. Then he constructed a 2 kW-700 mm-diameter pad which has horizontal radial tolerance of 130 mm with a 200 mm air gap. Mizuno *et al.* [67] proposed the use of magnetoplated wires to improve the transfer efficiency. Magnetoplated wires are actually a copper wire whose circumference is plated with a magnetic thin film, thus the resistance caused by the proximity effect will decrease. Zhao *et al.* [68,69] proposed a double-layer printed spiral coil structure as well as its theoretical model, which can utilize the space more effectively and provide a larger parasitic capacitance for lower resonant frequency applications.

High quality factors are an important research hotspot which actually determine the whole system transfer characteristics. The external capacitor is usually not used due to their losses, which will reduce the quality factor, and in turn decrease the efficiency of the systems [76]. The maximal quality factor at the resonant frequency (which should be also the system operating frequency) is the SCMR system design objective, because it can improve the transfer efficiency despite long transfer distances. Generally, there is only one maximum quality factor with corresponding frequency, hence, we must make the coils resonate at the operating frequency that must coincide with the frequency where they exhibit maximum quality factor [76,77]. Additionally, Jonah *et al.* [70] deduced the calculation formulas of crucial parameters based on maximizing quality factors, which had given many meaningful guidelines for the optimal design of SCMR system elements. Equations (17) and (18) also show that the tight coupling situation is reached only when the quality factors are very high. Marin Soljacic [5] mentioned that the theoretical quality factor for the loops is estimated to be 2500, but the measured value is only 1000 due to the skin effect (the frequency is 10 MHz). Fortunately, higher resonant frequency with optimization methods [70] can be used to improve the quality factor, and, hence, transfer efficiency. On the other hand, quality factors could be enhanced by decreasing the resistance of the coil. Although the adoptive methods are different, the ultimate goals of new spatial layout structure [64], magnetoplated wires [67] and high-temperature superconducting (HTS) transmitter antenna [65] are actually the same, which are to decrease the equivalent resistances of the coils and improve the system transfer efficiency.

The aforementioned optimization methods all aim to improve the transfer characteristics, but some important optimization parameters, such as quality factor and mutual inductance, conflict with the weights, volumes and costs of the coils, thus the optimization process must be a tradeoff. Moreover, the shielding design of SCMR should be paid more attention because the effects on human beings caused by high frequency magnetic fields are unclear, and few studies can be referred to. The magnetic field cancellation method by using a reactive resonant current loop is instructive [92]. Another important item is the selection between lumped capacitance and parasitic capacitance. If the lumped capacitance is used, the additional losses due to its equivalent series resistance (ESR) and the contradiction between its withstand voltage and the quality factor of the coil should be considered seriously. If the parasitic capacitance is used, the withstand voltage and ESR problems can be ignored, but the sensitivity problem of parasitic capacitance caused by surrounding objects should be emphatically considered, because this will affect the system resonant frequency sharply. Besides, different winding structures (helix, spiral and *etc.*) of resonant coils may have great effects on the system transfer characteristics, so comparative studies are necessary.

3.3.2. Optimization Design Flow

Jonah *et al.* [70] proposed 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. Hasanzadeh *et al.* [71] proposed 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. In [72,73], 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, Kiani *et al.* [25] proposed an iterative design methodology which can optimize geometry parameters to improve transfer efficiency. And they further presented a new figure of merit (FoM) [74], 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

SCMR 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 economical burden and physical pains on patients. Fortunately, SCMR is appropriate to solve this tough problem. Li *et al.* [37] proposed 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. Chang *et al.* [78] pointed out that batteries can be replaced by this novel technology, the energy for implantable devices can be supplied wirelessly. Xu *et al.* [79] presented 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, SCMR 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.* [80] pointed out that SCMR can be used in underwater detection and illumination. Kim *et al.* [81] 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.* [82] mentioned that SCMR 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 [72,73,83,87]. 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 [94,95]. 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*.

4. Future Trends

The reasons why SCMR transfers power wirelessly with high efficiency over long distance can be explained as follows: Due to the use of parasitic capacitance, the operating frequency can be as high as megahertz. Consequently, the quality factors are very high, which can alleviate the sharp decline in transfer efficiency caused by the reduced coupling coefficient. In addition, the system architecture with four coils introduces another two adjustable freedom degrees, which can be used to optimize the transfer characteristics. The aforementioned conclusions are based on CMT and CT, but fundamentally, SCMR is an electromagnetism conversion process, so the principle interpretation with electromagnetic theory needs to be further studied. Besides, some technologies of IPT mentioned in Section 2.4, including decoupling circuits [96], DC equivalent analysis [97], tuned point detection [98] and LCL tuned network [99], can also be applied in SCMR. Thus we consider that SCMR and IPT will coalesce in the future despite their current distinctions.

Impedance matching is a key problem of SCMR, good performances usually accompany complex engineering structures, so a trade-off must be made in accordance with practical situations. At present, impedance matching researches mainly focus on the driver source and the receiver terminal. The driver sources used in SCMR are generally Colpitts oscillators [5], Class-E amplifiers [100,101] or some other RF amplifiers, which can be used to realize impedance matching by optimizing their circuits. However, their efficiencies, radiation and costs should be considered carefully because of the megahertz operating frequency. The receiver terminal usually includes the resonant network, rectifier and DC/DC converter, which can be used to execute impedance matching by optimizing the circuit topologies and corresponding control strategies. Furthermore, the multiple matching based on merging respective merits of different methods is also a promising solution. The tuning or matching methods which can achieve unity power factor and simultaneously maintain high transfer efficiency are valuable to be studied. And it is suggested that unity power factor should be satisfied first, and then the transfer efficiency.

System design, including system parameter selection, impedance matching realization, control strategy design, cost-benefit assessment and so on, is actually a global optimization process with the purpose of satisfying practical demands in engineering and improving transfer characteristics. Determining how to overcome the bad effects on transfer characteristics caused by system parameter sensitivity or surrounding objects are also worthwhile to be further studied. Ferromagnetic materials as well as its optimization design can be introduced to improve mutual inductance between adjacent coils, but it probably limits the operating frequency, and additional hysteresis losses and eddy-current losses should be taken into consideration. Additionally, due to the nonlinearity of B-H curve of ferromagnetic materials, the inductance value of the coil with a ferromagnetic core will change if the operating current is too high, this unwanted phenomenon should be avoided by the predesign.

In order to realize impedance matching and further maintain system stability, a closed-loop control system with good performance is necessary. There are roughly four important problems which should be considered in this control system design, including how to estimate the condition of the load precisely, how to realize the electronic or mechanical impedance matching actuators, how to keep the feedback adjusting speed follow the change of the load, and how to improve the dynamic response, stability and robustness of the system effectively. Additionally, the sensitivity problem caused by the megahertz operating frequency should be given sufficient attention, and corresponding research should be conducted. For high power level applications, the effects on the power grid caused by high chopping frequencies should be also studied.

As we know, the higher the operating frequency, the higher the transfer efficiency. However, high frequency may bring a certain amount of electromagnetic radiation, its frequency or intensity probably determines if there are effects on human beings. If wireless power transfer system with high operating frequencies is going to be applied in practice, shielding design is an urgent problem. Furthermore, the measure and evaluation criteria of electromagnetic field intensity are also crucial. Presently, there are many associations and scientific research organizations which study the effects on creatures caused by this radiofrequency electromagnetic field [102–104], but until now, there are no direct and sufficient evidences which can prove that radiofrequency electromagnetic field has bad effects on biological histocytes [105]. Additionally, exposure to 20 kHz, 0.2 mT (RMS) or 60 kHz, 0.1 mT (RMS) sinusoidal magnetic fields shows no reproducible, reproductive and developmental toxicity for mammals [106]. In order to promote the commercialization process of SCMR, associations, scientific research institutes and standardization organizations should collaborate to formulate corresponding design, manufacture and evaluation specifications.

5. Conclusions

This paper has reviewed wireless power transfer via SCMR, 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 SCMR 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 SCMR and IPT are identical, despite some distinctions between them, so mutual learning and assimilation between SCMR 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. SCMR 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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Author Contributions

Xuezhe Wei and Zhenshi Wang collected corresponding references and finished the writing of the paper, Haifeng Dai revised and improved it.

Conflicts of Interest

The authors declare no conflict of interest.

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