International Journal of Scientific Engineering and Research (IJSER)
ISSN (Online): 2347-3878
Index Copernicus Value (2015): 56.67 | Impact Factor (2017): 5.156

A Critical Review on WPT for Midrange Operation

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Abstract: ***Wireless power transfer via magnetic resonance coupling method has opened a new possibility to the electrical system. It allows the possibility of power transfer in critical locations without wire. However, although the efficiency of power transmission is relatively high, the efficiency still depends on some of the critical factors. There have been several researches on methods to maintain power transmission at the highest efficiency. However, in such systems, some of the parameters are taken care of for the successful high power transfer efficiency (PTE). Therefore, it has come to attention that parameter estimation is a crucial factor to implement a successful WPT system. This paper presents a review on the critical factors of midrange wireless power transfer.***

Keywords: Wireless Power Transfer, Coupling Coefficient, Frequency diversity

1. Introduction

Wireless power transfer (WPT) is a breakthrough technology that now substantially gaining more interest due to their contribution in technical fields such as medical science [1, 2], electronic [3, 4] and automobile industry [5-7]. A WPT system majorly consists of magnetic coupled coils and matching circuits. The magnetic coupling between the transmitter (TX) and receiver (RX) actually depends on the input and output impedance condition which is inversely related to the distance [13]. Generally, the tunable LC matching circuits are used to transform the overall circuit impedance, but using lossy matching networks increases the power loss and lowers the efficiency. In this study, a critical analysis of WPT transfer at midrange operation is brought into account for further research.

Until now, many efforts have been made to improve the WPT technology as well as its application which can be classified into three categories: electromagnetic induction [8-10], magnetic resonance [11-13], and microwave power transmission [14, 15]. Among these, magnetic resonant coupling is most suitable for WPT applications due to its high transmission range and efficiency compare to the induction coupling and microwaves. In resonant coupled WPT, the transfer distance is actually limited due to reduced magnetic coupling with the axial separation between TX and RX coils. The effect of low couplings can be somewhat compensate by employing high-Q ($Q = (1/R)\sqrt{L/C}$) TX/RX coils [16]. However, due to the ohmic losses of wire and loading effects of source/load resistances, the achievable Q-factor of practical WPT coil becomes limited. Furthermore, high Q-factor cause the magnetic field of the circuit to rise due to high reactance and may cause adverse effects on human body [21].

Another issue regards the WPT performance is the design of TX circuit [22]. In general, Class-E power amplifier (PA) is used with the TX circuit which requires a single transistors to achieve zero voltage switching (ZVS), makes the system simple and inexpensive [23]. Compare to other classes, it is more sensitive to the output impedance, requires less components with high reliability [17, 18]. In WPT, Class E PA is also used with a great of its achievement [20, 22]. Coil alignment, load variation and distance are some common factors in WPT for weaker transmission [24], Uses of PA in WPT could resolve the good amount of power in worst cases. In this work, a Class-E PA is designed along with the matching circuit which includes TX coil as his load. Considering consumer electronics, three coils system was adopted for a longer distance.

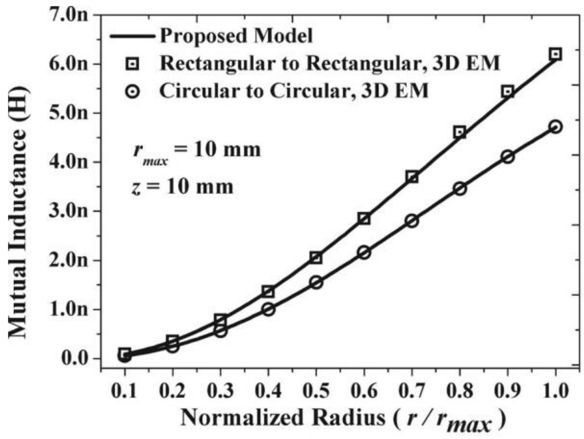
The paper is reviewed about the factors need to bring into account for further research in a literature review.

2. Critical Factors for Efficient WPT

WPT are mostly critically reviewed either in search of maximum power transfer or maximum energy efficiency. Besides, the maximum distance for minimum input power for maximum output can also be discussed. From RLT method, A perfect impedance matching can be shown the maximum power transfer of 50% which has discussed earlier in this chapter. Concerning that the design method must be a good choice of maximum power transfer method to meet the high power transfer application. There are several critical factors involving with MRCWPT where the most significant physical and geometrical parameters are analyzed.

2.1 Coil Design

Fundamental WPT depends on the designing coil, shape and their alignments i.e. the power transfer efficiency (PTE) depends on the coil size, shape, alignment and their materials. Litz coil are almost 20% more efficient compare to conventional copper coil [1]. Also the ratio of the primary and secondary coil diameter varies the power transmission air gap between them. Unlike coil radii and spacing the alignment must be consider a critical issue into the WPT. Except for multi coil transmission, lateral of angular misalignment of coil [2] could cause a serious degradation of PTE in almost all types of WPT. The coil alignment and optimum coil size is found through the following equation [3]; $R_{optimum} = \sqrt{2z}$, where $R_{optimum}$ is the optimum radius of the transmitting coil and 'z' is the distance between the transmitting and receiving coils. As square of the coil turn number is almost proportional to the reflected resistance into the primary side so that a higher value of transmitter is required to design for the maximum PTE [4]. Fig 1.1(a) shows a deviation of mutual inductance change with the change of coil radii and shape.



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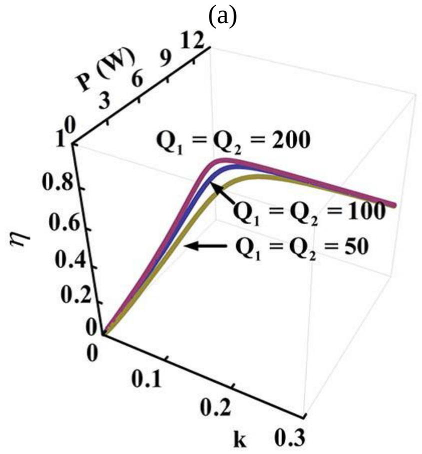

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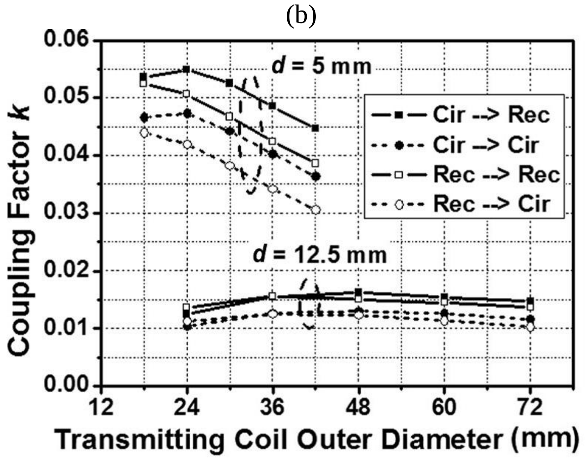

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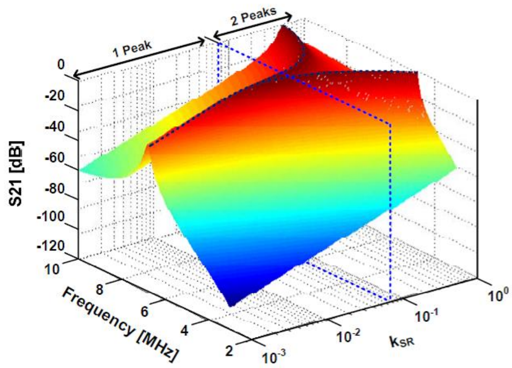
Figure 1.1: (a) Deviation of Mutual inductance due to different coil radii and shape [5] (b) Q factor analysis of overall condition of Efficiency, Transferred power and coupling co-efficient. [6] (c) coil radius versus efficiency and gain [7]

In Figure 1.1 (b), the effects of high-Q show an excellent improvement of η at the critical coupling. From Eqn. (2.40) the effects would be recognized clear mathematically. In WPT, Minimum circuit Q could be analyzed further for better PTE [8]. However, the coil geometry is still considered for further research and developments due to the different shapes (Spiral coil, flat coil, square coil, and circular coil) that are affecting different PTEs. As the coil turn number and its parasitic resistance directly related to the efficiency, designer must choose the appropriate turn number to reach the desired inductance, from Figure 2.16, the critical coupling condition exhibits the relation with turn number. Also from RLT, the effect of deviation of parasitic resistance of the coil can straightforwardly be observed [4].



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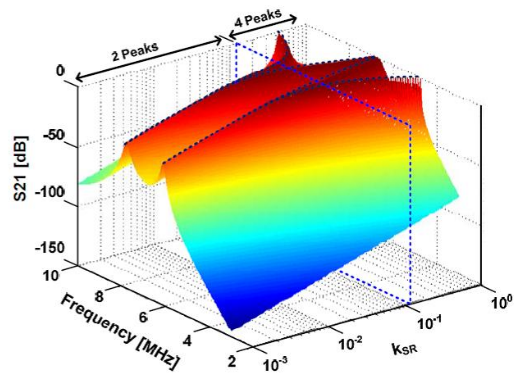

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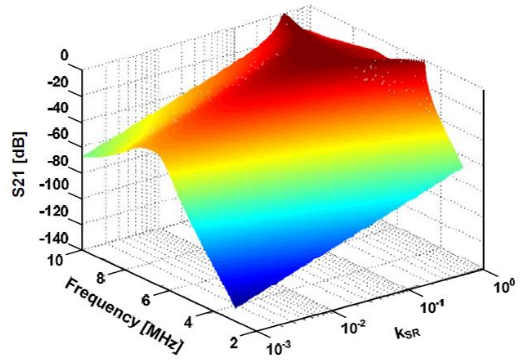

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Figure 1.2: Coupling condition due to the coil turn number [9] (a) Under coupling (b) Over coupling and (c) critical coupling condition

2.2 Material Study

Unlike the copper wire, Litz wire is widely used for coil design. Besides the litz wire, magneto plated wire is also used for different analysis to achieve the maximum PTE. Unlike the litz wire, which has proven the certain quality of PTE, meta-materials are also a good choice in WPT[10] the high Q is possible with the meta-materials that can further increasing the PTE[1]. The negative refractive index and evanescent wave amplification factor can particularly control the surrounding flux distribution. In recent years, high temperature superconductor (HTS) [11], shows the increasing of the efficiency for 2 resonators or multi coil but the transfer distances failed to increase significantly. So that, for efficient PTE at WPT, the material studies is required for appropriate methodology.

2.3 Coupling Coefficient

There are 3 coupling condition shown in Figure 1.3, where each of them exhibits different properties, in under/over coupling condition, the frequency splitting occurs. A serious degradation of power loss occurs at operating point rather than of that Splitting resonant frequency. From Neumann's Law, a slight increase of coupling coefficient can increase the induced voltage into the secondary side and thus increase the gain or transfer efficiency. Strong Coupling Magnetic Resonance (SCMR) and Weak Coupling Magnetic Resonance (WCMR) are both useful of transferring power in any WPT system. It is been observed in many experiments using the WCMR between the repeaters to increase the distance while the coil-loop distance remain fixed at the critical coupling condition which exhibits a SCMR [12]. Adaptive coupling between coil-loop-loop-coil (4-coild) and multi coils (3, 4, 5 etc. number of coils) can consider for further maximizing the efficiency to find out the possible critical coupling in different cases. Deviation of coupling coefficient will cause a mismatch of impedance and thus effect of loss into the system[13]. Auto tuning of impedance matching into the maximum power transfer method could reduce the effect of change of coupling coefficient from the critical point of any operating frequency. Cross coupling between multi coils still get some effect on PTE, however the effect could be worst if the optimum load is not selected carefully [14].

2.4 Impedance Matching

The effect of impedance matching is very common into any transmission system. In WPT, operating frequency is been chosen with respect to efficiency maximization and system power transfer and is limited by the coil design. High frequency uses for operating frequency like microwave transmission, the distance could be covered longer with low power and vice versa. In WPT, the characteristic impedance of 'χ' could be written as [15]; $\chi = \omega_0 \kappa_{12} \sqrt{L_1 L_2}$ where ω0, κ12, L1 and L2 are the resonant frequency, coupling coefficient, primary and secondary coil inductance respectively. Thus, increasing coil distance will decrease the coupling coefficient and mutual inductance as well as the impedance parameter. This mismatching can be compensated by considering Impedance Matched Network (IMN). IMN can be developed through L/Π network (2/4 coil transmission) to compensate the matching both in transmitting and receiving sides[16].

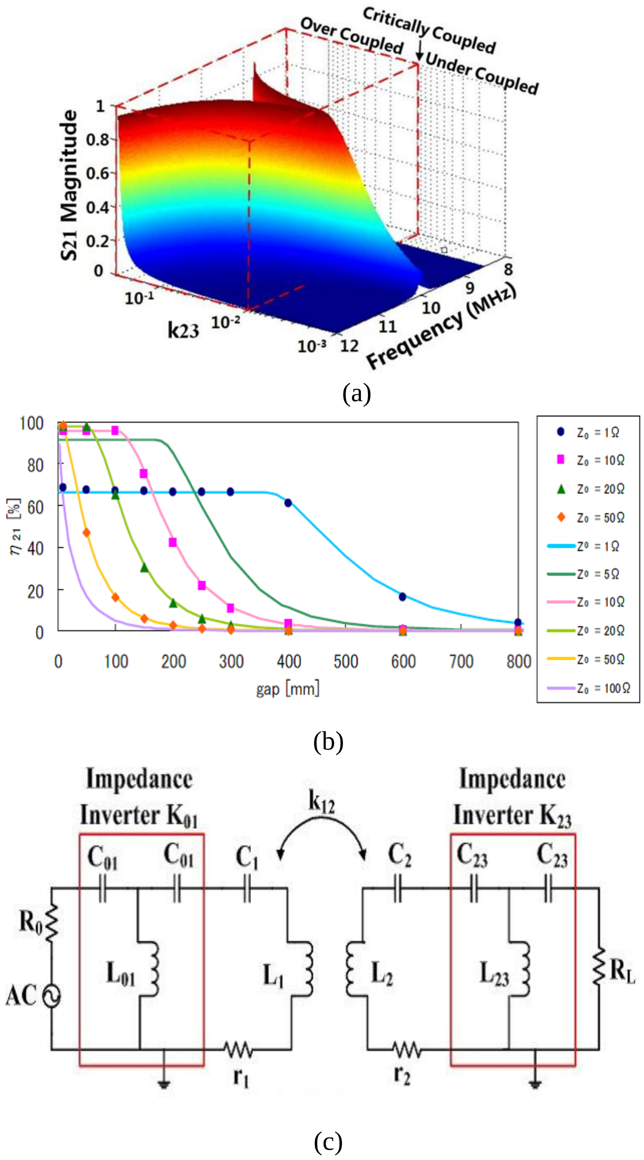

Figure 1.3: Effects of (a) Coupling coefficient[17] and (b) characteristic impedance versus efficiency [16](c) Impedance inverter equivalent circuit[18]

A popular method of impedance matching is to consider an impedance inverter to invert all the shunt resonators to series configuration and find the impedance matching both in input and output sides, In [18] the novelty of the methods considered into the multi receiver coil model to describe the effect of power division analysis in each step as well as handling capability of multiple impedance parameters. The next phase of the WPT applications require an auto matching of the impedance for multi receiver.

In many methods adaptive impedance matching effect is analysed to increase the PTE, The possible choice of L/ Π network are limited for series/parallel topology. Impedance matching coupling coefficient could also a feasible solution to achieving maximum distance of power transfer where in [19] the effect of impedance inverter is considered into coupling coefficient. The choice gets priority due to its simplicity for better understanding of other parameters relating to the coupling coefficient like (Q factor, Coil size, Coil inductance and parasitic capacitance as well as operating frequency). Besides of matching network, additional circuitry like a DC-DC converter could be used for matching impedance without changing the load resistance [20]. In IMN, the scope is still open for the dynamic case of impedance matching. In a closed system WPT[21] it is possible to maintain an auto-tuning procedure (describes with relay switching) but considering a continuous communication between the transmitting sides, However in Maximum Energy Efficiency Tracking (MEET), introduced of tracking the minimum input power for any required output and does not require a continuous communication between coils, thus the experimental analysis by choosing the optimum load impedance in MEET provides an advantage over closed system WPT [21] For any two port network, A, B, C and D are the characteristic impedance parameter, Vi, Ii are the voltage and current for the source and load (i=1, 2) then the relation can be brought from figure 10(c) as; $\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_2 \\ I_2 \end{pmatrix}$ and the matched impedance of $Z_{source} = \sqrt{AB/CD}$ and $Z_{source} = \sqrt{BD/AC}$ where, The effect of the transfer efficiency can be shown from the following figure before and after matching the IMN;

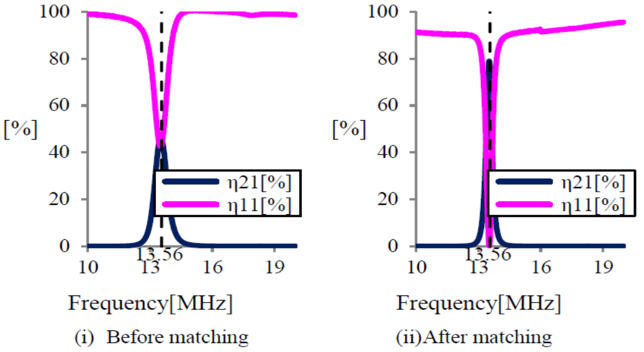

Figure 1.4: Effect of IMN in WPT [19]

The experimental analysis in Figure 1.4 shows a decrement of η11 minimum 10% after using the IMN. The technique of considering load monitoring could also improve the WPT system to avoid the error of selecting optimum load. One of the characteristic impedance is shown in Figure 1.5. The error equation with respect to source is found [22];

$$\frac{\partial Z_L}{\partial V_S} = -\frac{(\omega L_{m,12})^2 I_1}{(V_S - Z_{in} I_1)^2} \quad (1)$$

Though MRC is promising to the zero properties of image impedance, but still the properties cannot be neglected due to the effect of mismatched impedance. So that, an image impedance matching [23] could be studied further for the MRCWPT.

2.5 Frequency Diversity

For a strong coupling condition, when the coils are brought close together or the weak coupling condition, when the coils are taken far from each other then, the frequency splitting phenomenon could took place. System architecture with multi-relay, multi-transmitter and multi-receiver coils, if neighboring two or more resonant coils are brought in close proximity that their magnetic fields are relatively strongly coupled then frequency splitting may be occurred too [24]. Though the reflected impedance is lower than to the input impedance but in over coupled (mostly)/ under coupled region the effect of the reflected impedance is higher than input impedance. This effect happens due to the increased coupling coefficient, so that the effect occurs into the operating frequency and started to deliver power in different frequency. This phenomenon is well known by frequency splitting. In Fig 1.5, shows the effect of changing resonant frequency by the effect of load, for the higher Q-factor the resonant frequency becomes more difficult to In splitting [9], four resonant frequency is under different coupling condition. From the previous discussion, the coupling coefficient relates with the frequency diversity, thus the effect can further be implemented rather suppressed. In many multi transmitter/receiver or repeater systems in MRCWPT, the deviation of coupling coefficient from its optimum point can be traced out and then the operating frequency can be obtained at that point to obtain the maximum PTE [14]. For any 2 coil MRCWPT, possible adjacent operating frequencies can be found as;

$$\omega_{1,2} = \sqrt{\left(2-Q^{-2}\right) \pm \sqrt{\left(2-Q^{-2}\right)^2 - 4\left(1-\kappa_{12}^2\right)} \Big/ 2\left(1-\kappa_{12}^2\right)} \quad (2)$$

where, ω1=ω2, κ12 is the coupling coefficient, Q is the quality factor.

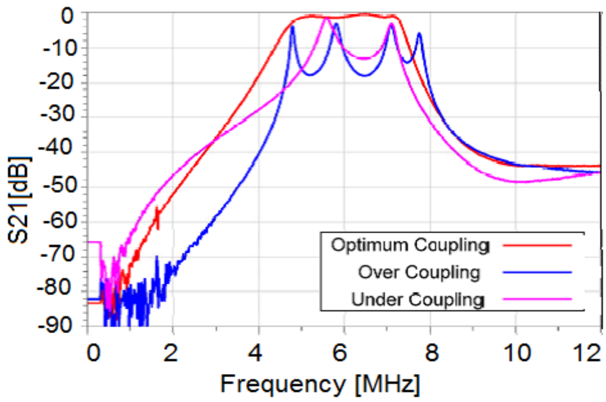

Figure 1.5: Frequency splitting phenomenon [9]

So, further scope of research lies to study on the different arrangement of system architecture to analyze the frequency splitting and its utilization.

2.6 Multiple Transmitters/Receivers Design:

In consumer electronics and commercial applications WPT could be designed to need of multiple TX and RX. Developing the multiple phenomena in WPT application will bring a challenge to the future works, where a lot of parameters need to be handled firmly with its resonant point. A frequency splitting may occur due to simultaneous coupling adjustment of TX and multiple RX coil. So, the efficiency of WPT could further be enhanced using impedance inverter method, which is aptly considered for the analysis of multiple TX of RX design[25]. In [26], a methodical study shows the effect of using multiple TX/RX in WPT system compare to the single coil, due to multiple TX the RX coil could have an effect of difficulties to obtain a critical coupling situation and thus the PTE could be degraded, But multiple RX is convenient to use to improve PTE. In [27], a vector control mechanism is derived in contrast with the conventional power division method and reported the increase of PTE using two TX coil. PTE depends on several parameters as well as load impedance; increasing the repeater thus effects of loading into the TX side and thus the transmission distance can achieved higher but due to the coupling effect of the added coil degrades the maximum power transfer. Multiple resonant frequency may arise due to the multiple RX and thus from Eqn. (2), the choice of appropriate resonant frequency can be chosen. A further analysis of repeater coil or multi coil transmission can be seen in[28-31]and achieved the maximum PTE in multi coil transmission principles. Besides the above discussion on critical factors, Environment is also a critical issue which must be considered for MRCWPT, Effect on temperature and humidity could cause a serious degradation of PTE. Mostly, the frequency range of the MRC is been chosen into the MHz range and required a power amplifier (PA) to enhance the field, the loss of PA is obvious into the higher temperature and would cause an unnecessary power loss into the system as the radiated heat. The conduction loss into the wire (I2R) also need to be analyzed for bigger coil and their materials, such as, the conduction loss of litz wire is higher than that of the copper wire. But the magnetic field enhancement is better into the litz wire provides almost 20% better efficiency [32]. Also the mutual resistance effect due to the uses of core into the coil. A feasible study of 5m off-distance shows the uses of core inside the hollow coil[33]. However, the choice of operating frequency is also a very important consideration for higher PTE. For the MRC, due to skin effect and proximity effect the increase of winding resistance may effect of higher frequency [34].

3. Conclusion

WPT systems based on magnetic resonant coupling are studied into the literature aspect to enhance the prominent findings and their corresponding critical survey. A thorough study assessing the compliance with midrange operation of WPT has been carried out revealing critical factors and its possible care to be taken of WPT technology.

4. Acknowledgement

This research work is supported by the ‘Bangabandhu Fellowship (Under Bangabandhu Science and Technology Fellowship Trust)’ sponsored by the Ministry of Science and Technology, Bangladesh.

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