Magnetic resonance coupling wireless power transfer for green technologies

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ABSTRACT

Wireless power transfer (WPT) is a technology that is considered the focus of scientists' attention for its development and creation to be compatible with many devices that are used today and also consider one of the green technology apps which means any technology can reduce the effect of people on the environment which is today grow continuously. In this paper, a wireless power transfer for a mobile charger had been discussed to get a maximum power and efficiency power transfer. WPT is considered as a reliable technology, efficient, fast, not using wires, and can be used for short and long-range. There are three methods for WPT, electromagnetic induction, magnetic resonance coupling, and radio waves which are classified by the distance that sends the power. Magnetic resonance coupling is the method that has been focused on in this paper because of compatibility with short or medium distances as battery chargers which depend on the magnetic field to transfer power without wires that can protect devices from damages and heating. As result the effect of distance on efficiency has been discussed with reached to nearer distance can improve efficiency however by using magnetic resonance technique, acceptable efficiency can be obtained with appropriate distance.

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1. INTRODUCTION

Wireless power transfer (WPT) is an important and major transition in power transfer technology that enables an energy transmission from a power source transmitter to a load receiver through an air gap without cables. Recently, WPT evolving significantly and is considered the main technique that can be used to transmit power wireless and change the conventional transmitting technique using cables. WPT technology has many features; Firstly, further develops ease of use as the bother from interfacing links is eliminated. Secondly, WPT is reliable, safe, low cost, and can be used for short and long-distance with various applications such as portable devices, electric vehicles, medical technology, and so on. Thirdly, protects from overcharging problems and minimizes the energy used. Moreover, enhances flexibility especially for devices that need replacement batteries or expensive charging [1], [2]. There are two types of this technology depending on distance "Near field techniques" that can transmit power for low and medium distance and "Far-field techniques" that can transmit power for long distances.

The prototype of WPT is the power source, transmitter circuit, receiver circuit, and load, for an energy transmitter an electric field or electromagnetic field can be used for inductive power transfer, because of all the features that WPT technology has was necessary to develop and update the technology so the main of this updates is QI standard has been released which works in the principle of WPT with some useful updates for mobile application charger but still grown and will be used for many applications soon with improves in the efficiency and distances [2]. Figure 1 shows the schematic diagram of the wireless power transfer system, the left side is called the transmitter and the right side is called the receiver side, E is a dc input source for WPT. R1, R2, C1, C2 are parasitic factors of the circuit. L1 and L2 are self-inductances, $\mathcal{M}$ is the mutual inductance between L1 and L2. C_{out} is the output capacitor for smoothing voltage, RL is the load resistance a resonant transformer means there is a compensation circuit (C1, C2) to the primary and secondary coil (L1, L2).

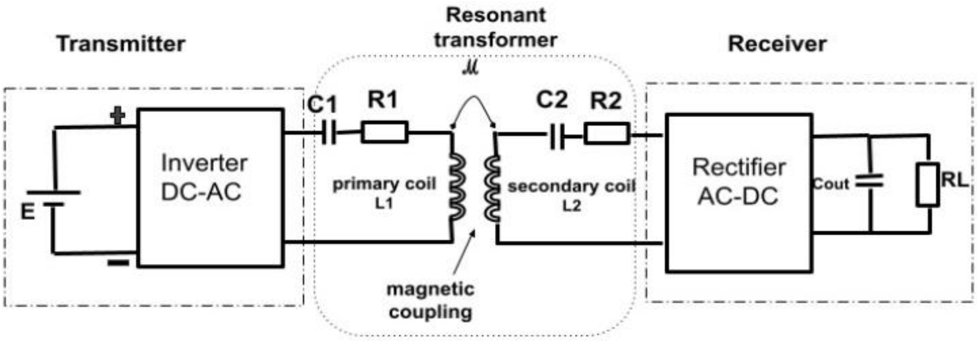

Figure 1. A model magnetic resonance coupling wireless power transfer system

2. WIRELESS POWER TRANSFER (WPT)

WPT is as discussed an important technology that can transmit energy between transmitter and receiver without any contact. The main common feature is that all methods transmit power using alternating current (AC). Generally, transmitting power can be in two methods, coupling and radiative. The coupling method is classified into a magnetic field and electric field whilst the radiative method is classified into microwave lasers. While magnetic and electric coupling worked in near field type which means transmit power in short and medium-range whilst radiative work in far-field type [3], [4].

3. MAGNETIC RESONANCE COUPLING (MRC)

Magnetic resonance WPT considered as a non-radiative method is suitable for short and medium distances, so the focus on MRC has become more, especially for portable devices, as gives high power and efficiency compared to a magnetic inductive method (without resonance). The operation principle of magnetic resonance WPT is to compensate the primary and secondary reactance in coils means there is a two capacitor and inductance resonator (LC) as called a compensation circuit which is also called tank circuit consisting of inductor L and capacitor C. LC circuit divided into serial-serial (S-S) and parallel-parallel (P-P) this classification depends on the method capacitor connection to inductor but these two connection is given the same purpose so an (S-S) connection shown in Figure 2 [4]-[6].

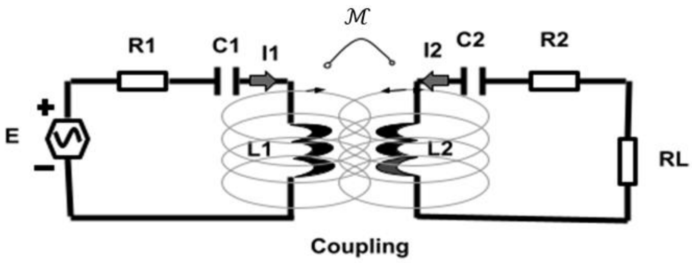

Figure 2. The basic circuit of magnetic resonance coupling

When an AC is flowing through the transmitter (Tx) coil a magnetic flux is delivered as shown in Figure 2. The Rx coil is then getting this flux and is changed over into an AC voltage across it while the main feature of this transfer type is transmitting power with high power and efficiency than other types of coupling because the compensation circuits prevent or reduce the reflected power and reactance as shown below in mathematical calculation [4], RL load resistance which is receive the power from Tx side that can considered as any device such as mobile phone which need a dc voltage to charge so a rectifier is added to convert AC-DC voltage as shown in Figure 1.

$$Z1\, I1 + j\omega\mathcal{M}12I2 = E \quad (1)$$

$$jw\mathcal{M}12I1 + (RL + Z2)I2 = 0 \quad (2)$$

Where Xn = wLn - 1/ wCn, n=1or 2 is the reactance of the resonator, and Z= (Rn +jXn) is the impedance, E estimates input voltage, Tx is transmitter, Rx is receiver.

3.1. Reflected impedance calculation

From (2) obtained [3],

$$I2 = -jw\mathcal{M}12I1\, /\, RL + Z2 \quad (3)$$

by a substitute (3) in (1), input impedance has obtained as,

$$Zin = E\, /\, I1 = Z1 + w\mathbf{2}(\mathcal{M}\mathbf{2})\, 12\, R2 + RL + j\, X2 \quad (4)$$

The first term (R1 + j X1) is the impedance of the primary circuit, the second term is the reflected impedance that is seen by the power source due to the current induced in the secondary winding, the reflected impedance (Zr) is:

$$Zr = w2(\mathcal{M}2)\, 12\, R2 + RL + j\, X2 \quad (5)$$

and if the circuit is at resonance which X=0 then reflected impedance is,

$$Zr = Rr = \omega 2\, (\mathcal{M}2)12\, R2 + RL \quad (6)$$

Therefore, when systems operate at a resonance frequency of the secondary, reflected impedance becomes only resistive which means there is no reactance reflected the source as in the other method mentioned above, this feature is considered a good advantage of (s-s) WPT which gets a high power and efficiency to load [3].

3.2. Calculation of the efficiency (η)

The power transmission efficiency is defined as the ratio between the output power PMN to the input power PTX, the term MN stands for matching network. The efficiency calculation in the receiver is shown in [5], [6]:

$$\eta LRx = (Re[ZMN]\, iRX2\, /\, 2)\, /\, (Re[ZMN]\, IRX2 + (RRX\, iRX2/2)\,) \quad (7)$$

where iRX indicates the max current in TX and the Re [ZMN] is the real part of ZMN [6]

The result can be expressed as in (8), in terms of the quality factor of RX.

$$QRX = wLRX\, /\, RRX \quad (8)$$

While load quality factor (QL),

$$QL = wLRX\, /\, Re[ZMN] \quad (9)$$

So efficiency is;

$$\eta LRx = QRX\, /\, QRX + QL \quad (10)$$

And to determine η of TX need to determine ZTX,

$$ZTX = VLTX/\, iTX = [RTX + jwLTX] + ((w2MTX - RX2)\, /\, (RRX + jwRX + ZMN)\,) \quad (11)$$

where:

$$\eta LTx = (Re[ZRX - TXref]\ iTX2\ /\ 2)\ /\ (Re[ZRX - TXref]iTX2\ /(2 + RTXITX2/2)) \quad (12)$$

As (6) when the system operates at resonance get a small reflected reactance which leads to better efficiency, so:

$$\eta LT\,x = \left(RRx - T\,xref — RRx - Txref\right) + RTx = (\mathcal{M}Tx - Rx2QT\,xQRx - L\ /\ (\mathcal{M}Tx - Rx2QTxQRx - L + 1)) \quad (13)$$

Finally the total link efficiency [5], [6].

$$\eta Link = QRx - L\ /\ QL * \{\ kTx - Rx2QTxQRx - L\ /\ kTx - Rx2QTxQRx - L + 1\} \quad (14)$$

where k is a coupling coefficient,
Hence the power delivered to the RX circuit,

$$PMN = \eta Link * PTX \quad (15)$$

From the above equations seems that having a resonance circuit is important to maximize the real part of reflected impedance for getting an acceptable power and efficiency in load [6], [7]. In the paper, Tritschler *et al.* [8]-[11] can see some different ways to get high efficiency that need to transfer and charging devices.

3.3. Power and efficiency comparison between magnetic couplings types

From Table 1 shows that the power and efficiency become both high or acceptable values on the receiver side with the insertion of C_1 and C_2 (S-S) which is considered as a compensation circuit. The reader can see more details about (S-S) WPT in references [8]-[10]. While for more information about magnetic resonance coupling and detail about WPT for 5g application can see [12]-[17].

Table 1. Power and efficiency comparison [4]

	N-N	N-S	S-N	S-S
Power	Low	Low	High	High
Efficiency	Low	High	Small	High

N-N: No resonance (without C_1 or C_2).
S-N: Primary side resonance (C_1)
N-S: Secondary side resonance (C_2).
S-S: Resonance primary and secondary side (C_1, C_2).

For more information about multiple load in receiver can see in [18], [19], where several recent studies [20]-[24] talked about different techniques to how to design and get an acceptable result of power transferred wireless and show the result of different ways with simulation results. Also [25] is a modern study MRC- WPT system have suggested to test the effect of conducting medium on efficiency and get a result which is can a method to determine an appropriate frequency of WPT in conducting medium.

4. RESULT AND DISCUSSION

KQ product is considered an easy representation of maximum efficiency at the resonance frequency (**Fr**) so the results that obtained of the effect on maximum efficiency is shown below. Figure 3 shows that as the KQ product increases assume coupling coefficient **K** is a constant and high-quality factor **Q** of coils which leads to an increase in the efficiency of the power transmitter to the load or any device. Figure 4 shows that, quality factor affect by frequency and R (r of the primary and secondary coil) variation and because R1, R2 is increased due to skin effect as frequency increase which leads to decrease in Q so, maximum efficiency can be achieved when the circuit is used at the frequency at Q is maximum value with assuming K is constant because its change not noticeable.

It's clearly from Figure 5 max efficiency increased as the distance is decreased between coils which mean coupling factor increased, mutual inductance is also affected by k and L of coils so if k constant changing in L can affect or improve the mutual inductance which tends to improve the efficiency of power transmitter to the load as shown in Figure above better efficiency is at 1. Figure 6 show that at the resonance frequency 30 kHz maximum efficiency of 83% is obtained and at low or above resonant frequency efficiency become lower, also the max η changed with coupling coefficient which k=0.5 is considered a critical value. From Figure 7 can see max efficiency becomes lower than Figure 6 which is equal to 73% due to decrease in K or can say due to increase in distance between the Tx and Rx coils.

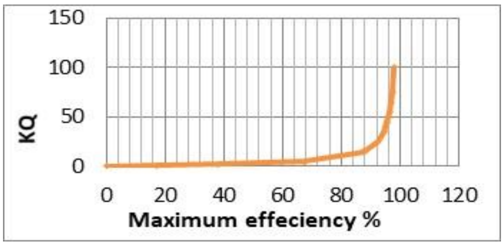

Figure 3. Maximum efficiency against KQ product

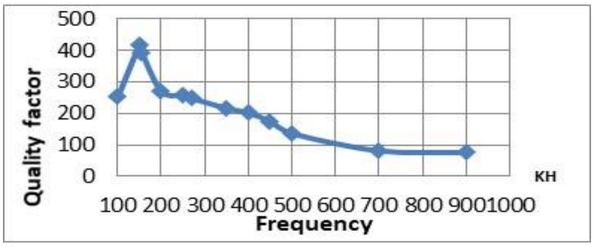

Figure 4. Quality factor versus frequency with R1, R2 variation

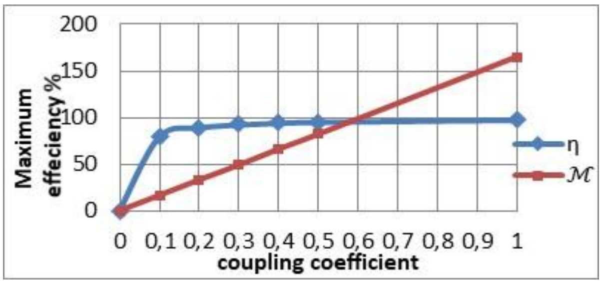

Figure 5. Maximum efficiency, mutual inductance against coupling coefficient

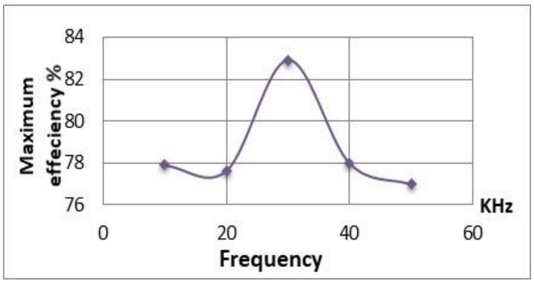

Figure 6. Efficiency against frequency at Fr =30 KHz, K=0.5

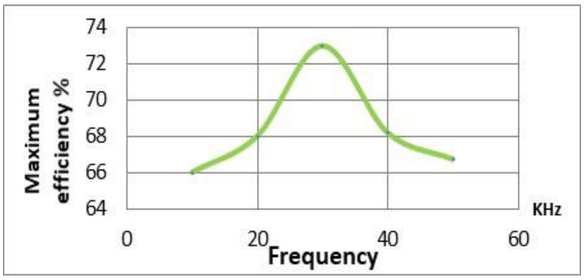

Figure 7. Efficiency against frequency at Fr =30 KHz, K=0.3

Figure 8 shows that max efficiency is 87.5 can be obtained at the resonance frequency, k= 0.7 which is considered acceptable distance and efficiency for charging some types of devices such as mobile phone. The results from Figure 3 to Figure 8 are distance and frequency can affect the efficiency of power transmitter also other parameters such as L, R but has a small effect compared to distance or coupling coefficient also the important things to have better efficiency is to choose appropriate resonance frequency to get good matching in the circuit which tend also to better efficiency. Figures 6-8 illustrate the difference in efficiency at different coupling coefficients and frequency, in figures above K=0.3, 0.5, 0.7 were chosen to compare between them tend to result that better efficiency can be obtained at k=0.7 at the resonance frequency, that's mean at the nearer distance the power transmitter efficiency becomes higher. This efficiency is acceptable for charging mobile phones at a good distance. These results can see it in short expressions in

Table 2. Table 2 shows the results in short expression to clarify the Maximum efficiency changing with coupling coefficient K equal, above and below critical value where K range is (0-1) and 0.5 is a critical value, so from result seems that as K increased tend to increase Max efficiency.

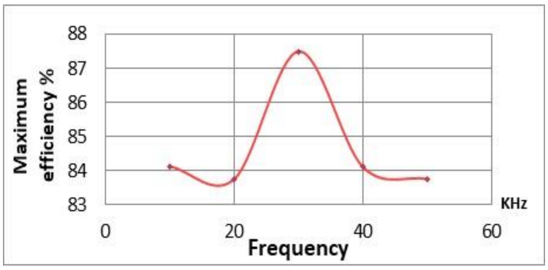

Figure 8. Efficiency against frequency at Fr =30 KHz, K=0.7

Table 2. Efficiency changing according to coupling coefficient variation

Coupling coefficient	K=0.3	K=0.5	K=0.7
Max efficiency %	73	83	87.5

5. CONCLUSION

WPT is a great technology that makes all things easy and safer which is also considered one of the green technology applications and as know, whenever power and efficiency are high, is better. From research on WPT has been reached that a magnetic resonance coupling (S-S) method is the better technique to have maximum power and efficiency to the load mid and long-distance with safety, however, there are some disadvantages of the WPT such that reduces the **P, η** when the distance is far but this type of technology still development and will become the first technology for a lot of uses such as electricity, electric vehicles, broadcast energy and so on, but now the popular uses of the mobile charger. The result that has been obtained in this paper is that frequency can affect the efficiency of the system by an effect on parameters, quality factor, coupling coefficient, and so on. Generally, in this paper the result that has obtained is frequency and distances can affect maximum efficiency however, the acceptable power transfer depends on the device that needs to charge it, and some sophisticated devices now depend on the technique (S-S) that talked about in this paper, with a control system which means can transmit power to the device then after full charge stop transmitting automatically which prevent the devices from damage. The expected in near future a wireless charging become within reach for a lot of devices including mobile applications, electric vehicles, electricity buildings and so on which is all called green technology.

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