Analysis of Relay Effect on Wireless Power Transfer

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Abstract: Witricity, the technology of wireless power transfer (WPT) over a limited distance via coupled magnetic resonances in the non-radiative near-field, has been the center of researcher's attention over the recent years. As the main concern about this technology, there has been great effort to transfer electricity over longer distances using resonant coil (Relay). However, despite all benefits and advantages of the resonant coils, they bring about some undesirable effects on the system which have never been considered to date. This paper provides an analysis on the results of a system with the resonant frequency of 2.8 MHZ.

1 INTRODUCTION

In 1889 wireless power transmission (WPT) was demonstrated by Nikola Tesla. He succeeded to transfer electricity to about a few miles. Wireless power transfer-based on strong magnetic coupling, known as witricity, has been considered by the MIT university researchers in 2007 because of its reasonable benefits and efficiency. The MIT researchers successfully transferred about 60 Watt over a distance of 7 feet (A. Tucker, 2013), (D. Gallichi Nottiani, 2012), (F. Zhang, 2009). Thanks to the recent significant progresses in this technology, the witricity has extended its applications to many other industries such as "feeding implant units" (X. Liu, F. Zhang, 2009)," feeding Endoscopy Capsuls", by making them smaller and portable (free-motion) (F. Tianjia Sun, 2007), charging Electric Vehicle wirelessly ((S. Li, 2014), (S. Sabki, 2007)), robotic industry, charging cell phones, wireless sensor networks, and RFID technology (J. Wang, 2010).

In this paper we try to analyze the effect of resonant coils on the transfer system. It will be discussed in this paper that while these coils increase the system efficiency, but they produce undesirable effects on the transfer systems. One of the main topics which has not yet been considered is mutual inductance in receiving and sending systems by the resonant relay.

This mutual inductance affects the main circuit (sender and receiver) inductance according to the position (location) of the resonant relay. Such changes in the system inductance deteriorate the resonant state of the system and weaken the efficiency.

This issue needs even more attention when the position of the resonant relay is not fixed and it moves between the receiver and sender.

A transfer system with resonant frequency of 2.78 has been designed and analyzed in this paper. The resonant frequency in each circuit is calculate using

$$f_{rp} = \frac{1}{2\pi\sqrt{L_p . C_p}} \quad f_{rs} = \frac{1}{2\pi\sqrt{L_s . C_s}}$$

$$f_{rt} = \frac{1}{2\pi\sqrt{L_t . C_t}} \tag{1}$$

To allow WPT the resonant frequency must be the same in all the circuits.

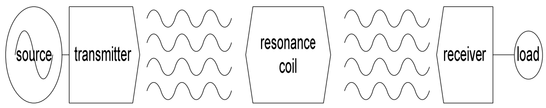

Figure 1: Scheme of relayed witricity system.

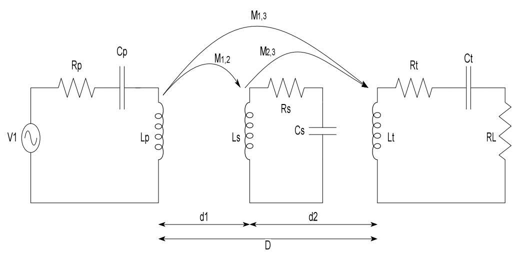

Figure 2: Thevenin equivalent circuit model.

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According to the coupling transformers principle, to a have resonant circuit, the product of inductance and capacitance in the circuits must be equal (T. Mohamadi, 2011).

$$f_{rp}=f_{rs}=f_{rt}\xrightarrow{=}L_p.C_p=L_s.C_s=L_t.C_t \quad (2)$$

To solve and analyze the circuit, the KVL law is applied to the Thevenin equivalent circuit of figure 2.

$$\begin{pmatrix}V_1\\0\\0\end{pmatrix}=\begin{pmatrix}R_p+j(\omega p-\frac{1}{\omega c_p}) & -j\omega M_{1,2} & -j\omega M_{1,3}\\ -j\omega M_{2,1} & R_s+j(\omega_s-\frac{1}{\omega c_s}) & -j\omega M_{2,3}\\ -j\omega M_{3,1} & -j\omega M_{3,2} & R_t+R_l+j(\omega p-\frac{1}{\omega c_t})\end{pmatrix}\begin{pmatrix}I_p\\I_s\\I_t\end{pmatrix} \quad (3)$$

Where, IP is current in the primary circuit, is denotes the current in the secondary circuit, It is current in the receiver circuit, and R1, R2, R3 indicate internal circuit resistances.

Due to the symmetric state of the system, i.e. M1, 2=M2, 1, M1, 3=M3, 1, and M2, 3=M3,2) and by replacing the self-impedance with Z factor, the following equation is obtained:

$$\begin{pmatrix}V_1\\0\\0\end{pmatrix}=\begin{pmatrix}Z_p & -j\omega M_{1,2} & -j\omega M_{1,3}\\ -j\omega M_{2,1} & Z_s & -j\omega M_{2,3}\\ -j\omega M_{3,1} & -j\omega M_{3,2} & Z_t\end{pmatrix}\begin{pmatrix}I_p\\I_s\\I_t\end{pmatrix} \quad (4)$$

By solving equation (4), the current of each circuit of each circuit is computed as:

$$I_p=\frac{Z_p.Z_t+\omega^2.M_{2,3}^2}{Z_p.M_{1,3}+Z_p.\omega^2.M_{2,3}^2+Z_p^2.Z_t+Z_t.\omega^2.M_{1,2}^2+2iM_{1,2}M_{1,3}.M_{2,3}.\omega^3}.V_1 \quad (5)$$

$$I_s=\frac{i(Z_t.\omega M_{1,2})-\omega^2.M_{2,3}^2.M_{1,3}}{Z_p.M_{1,3}+Z_p.\omega^2.M_{2,3}^2+Z_p^2.Z_t+Z_t.\omega^2.M_{1,2}^2+2iM_{1,2}M_{1,3}.M_{2,3}.\omega^3}.V_1 \quad (6)$$

$$I_t=\frac{i(Z_p.\omega M_{1,3})-\omega^2.M_{1,2}.M_{2,3}}{Z_p.M_{1,3}+Z_p.\omega^2.M_{2,3}^2+Z_p^2.Z_t+Z_t.\omega^2.M_{1,2}^2+2iM_{1,2}M_{1,3}.M_{2,3}.\omega^3}.V_1 \quad (7)$$

By calculating the current of the each coil, the produced and consumed powers are obtained,

$$P_2=R_s.I_s^2,\quad P_1=-V_1.I_p,\quad P_3=R_L.I_t^2 \quad (8)$$

Where, P1 is t power produced by his source. By replacing the current in the equation (8) and calculating the power for each circuit, the efficiency of the whole system is obtained:

$$\eta=\frac{P_3}{P_2}.\frac{P_2}{P_1}=\frac{P_3}{P_1}\Rightarrow \quad (9)$$

$$\eta=\frac{\left(\frac{i(Z_p.\omega M_{1,3})-\omega^2.M_{1,2}.M_{2,3}}{Z_p.M_{1,3}+Z_p.\omega^2.M_{2,3}^2+Z_p^2.Z_t+Z_t.\omega^2.M_{1,2}^2+2iM_{1,2}M_{1,3}.M_{2,3}.\omega^3}.V_1\right)^2.R_L}{\frac{-(Z_p.Z_t+\omega^2.M_{2,3}^2)}{Z_p.M_{1,3}+Z_p.\omega^2.M_{2,3}^2+Z_p^2.Z_t+Z_t.\omega^2.M_{1,2}^2+2iM_{1,2}M_{1,3}.M_{2,3}.\omega^3}.V_1^2}\Rightarrow \quad (10)$$

$$\eta=\frac{R_L.\left(-i(Z_p.\omega M_{1,3})+\omega^2.M_{1,2}.M_{2,3}\right)^2}{(Z_p.Z_t+\omega^2.M_{2,3}^2)\left(Z_p.M_{1,3}+Z_p.\omega^2.M_{2,3}^2+Z_p^2.Z_t+Z_t.\omega^2.M_{1,2}^2+2iM_{1,2}M_{1,3}.M_{2,3}.\omega^3\right)} \quad (11)$$

At the resonant frequency, the capacitive and inductive parts of the circuit eliminate and the circuit is purely resistive. Hence, the maximum efficiency is:

$$at\ :\ f_r\begin{pmatrix}Z_p=R_p\\Z_s=R_s\\Z_t=R_t+R_L\end{pmatrix}\xrightarrow{\eta_{\max}:f_r} \quad (12)$$

$$\eta_{\max}=\frac{R_L.\left(-i(R_p.\omega M_{1,3})+\omega^2.M_{1,2}.M_{2,3}\right)^2}{(R_p.(R_t+R_L)+\omega^2.M_{2,3}^2)\left(R_p.M_{1,3}+R_p.\omega^2.M_{2,3}^2+R_p^2.(R_t+R_L)+(R_t+R_L).\omega^2.M_{1,2}^2+2iM_{1,2}M_{1,3}.M_{2,3}.\omega^3\right)} \quad (13)$$

2 EXPERIMENTAL RESULTS

These tests are carried out on three different types of topologies in witricity and results also show a clear relationship and the validity between the theory and the formulas have been obtained before. We have also carried out a comparative study between the three types of series, parallel and topology modify without the resonant ring which can be found in each test in terms of power quality the results of each methods.

By doing experimental tests on these three different topologies mentioned before, as shown in figure 3. These three types of topologies have just used in the transmitter side of experiment. However, the topology of the receiver is fixed in all three tests also 20 cm distance between transmitter and receiver is considered and resonant ring moves between the two parts(transmitter and receiver) which is shown by the symbol d1 which mentioned in figure 2 and the results of this experiment are clearly shown in figure 6. For a comprehensive view on the issue, a comparative test have done, without the existence of the resonant ring this means that we change the distance between transmitter and receiver (D in figure (2), From the results it can be concluded that shown in Figure 7. It should also be noted that the load resistance of 50 ohms is considered.

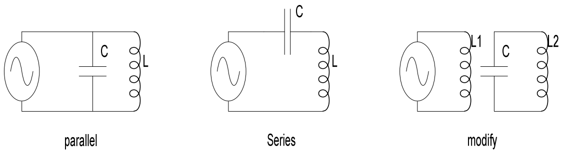

Figure 3: Windings of the transmitter.

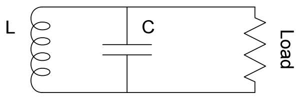

Figure 4: Receiver.

According to the equation (11), the resonant coupling increases the efficiency allows power transfer over longer distances. The effects of these coils on the efficiency are demonstrated in figure 5.

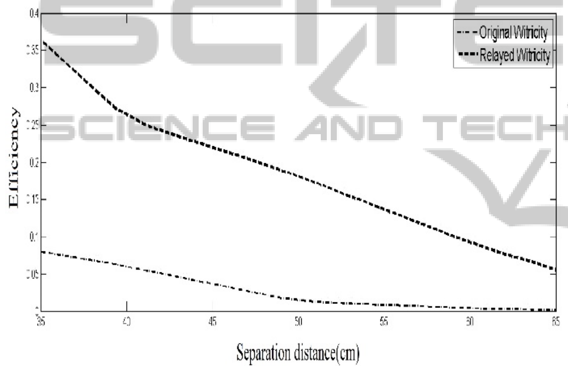

Figure 5: Experimental results of relayed and conventional witricity systems (F. Zhang, 2010).

In the next experiment according to the figure 2, we settled the sender and the receiver windings, at a distance of 20cm (D=20) and resonant ring will move between the two windings. At first, we put the resonant ring at the closest distance to the sender windings (d1<1cm) and then we gradually increase the distance and we calculate the efficiency during these situations and as derived from the results, proximity of resonant ring to each of the windings of the sender and receiver will lead to There has been a change in the parameters of the load and source which these changes will lead to the withdrawal of the resonant mode and it causes reducing the power transfer efficiency.

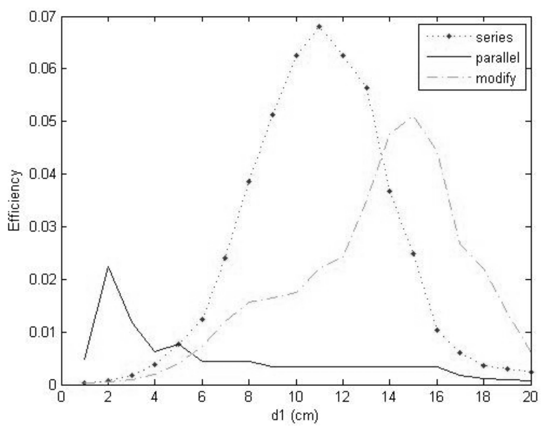

Figure 6: Resonant ring impact on the efficiency of series, parallel and modify windings.

The next test a wireless power transmission system (WPT) with three different topologies for transmitter, is analyzed and experimental tests shows that the maximum power occurs at close distance between transmitter and receiver. This experiment carried out in the absence of receiver coil is placed in the closest distance to the transmitter coil and the distance increases gradually up to 40 cm. As figure 7 shows, using the modify form of winding will achieve the greatest efficiency.

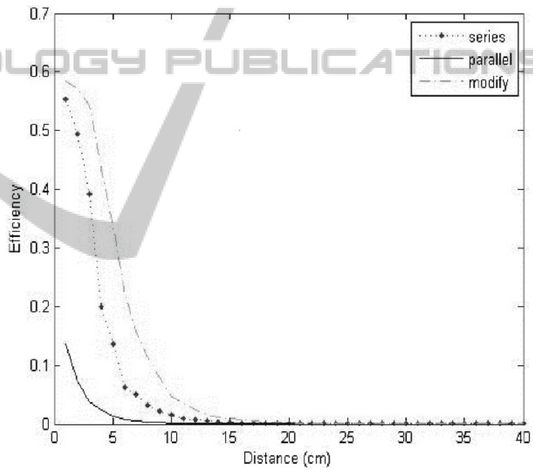

Figure 7: Comparisons between series, parallel and modify windings (considering D in figure 2) as distance.

Experimental results show as that when we increase the distance between receiver and sender into a point that no more voltage is induced in receiver coil (M1,3=0), a re-induction occurs at the receiver due to entrance of resonate relay. In this experiment it was noticed that when d1<d2, the efficiency increases. As a notable point, when M1, 3≠0, (i.e. when we have voltage on the receiver side even in the absence of resonant relay), by the entrance of resonant relay to the system, the inductive voltage increases as proved by the experimental equations (11). However, it is important not to reduce the values of d1, d2 too much. If this happens, the system will be out of resonant state due to the considerable changes in the inductance of both receiver and sender (see equation (3)).

3 CONCLUSIONS

In this paper, a WPT system with the resonant frequency of 2.78 MHz, and circuit capacitance of Cp= Cs=Ct=54.4 uF, and spiral coils with inductance of LP, Ls, Lt=0.602 uH and capacitor capacity of 54.4 NF was designed and tested to investigate the effect of resonant relay on the WPT efficiency improvement. On this study, the position of the resonant relay and its effect on the induced voltage as well as the MPT efficiency of such a system was also analyzed. Moreover, the limitation in choosing the resonant relays positions was also provided. The results of practical experiments on a system that has been made, clearly showed that using the resonant relay has been able to raise the voltage induction.

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