TEST Engineering & Management

November-December 2019
ISSN: 0193-4120 Page No. 5702 - 5708

The load Reliant Power Transfer of the Series-to-Series Inductive Resonant Wireless Power Transfer

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Article Info
Volume 81
Page Number: 5702 - 5708
Publication Issue:
November-December 2019

Article History
Article Received: *5 March 2019*
Revised: *18 May 2019*
Accepted: *24 September 2019*
Publication: *27 December 2019*

Abstract

In this paper, the effect of the output impedance to the power transfer efficiency of the series-to-series inductive resonant wireless power transfer at the resonance frequency is reviewed in details. The analysis is carried out by utilizing the theoretical inductive resonance wireless power transfer model using the MATLAB ® package. In this paper, the experiment is designed to confirm the highest power transfer efficiency is obtained at the resonance frequency for the given value of the coupling coefficient. Besides that, the experiment is also conducted to find the optimum load impedance for all given value of coupling coefficient. The analysis shows that the maximum wireless power transfer efficiency for series-to-series inductive resonant wireless power transfer is at the maximum peak when operational at the resonance frequency. In addition, the power transfer efficiency is improved by working at the optimum load impedance. The experimental set up is presented and the analytical results are reported.

Keywords: *Efficiency, Power Transfer, Wireless Power Transfer*

1. Introduction

The wireless power transfer technology has been used widely in many applications which require contactless or wireless power for example in biomedical devices. Another example is the highly integrated wireless powered battery charging circuit for medical application is presented in detail [1]. While in other applications the wireless power transfer technology has been used included powering the cellular phone battery [2], powering the electric car [3]. It is reported that the contactless instrument and measurement were successfully carried through wireless power transfer technology [4]. In such an application, the energy transfer from source to load is carried by loosely coupled coils. But, the wireless power transfer efficiency from the source to the load is degraded by the low coupling coefficient, the unmatched impedance between the load and the receiving coil; and the splitting of the

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ISSN: 0193-4120 Page No. 5702 - 5708

operational frequency with the resonance frequency of the receiving coil [5].

The low coupling coefficient can be the result of the distance between the coils and the disorientation of the transmitting and the receiving coils. In general, the farther the coils separated and the lesser coils orientated; the lower the coupling coefficient. The changes of coupling coefficient with the distance between coils resulting in unmatched impedance between the receiving coil and the load. In addition, the mutual inductance of the coils reduced by the reducing of the coupling coefficient. While the coil inductance increased by the reduction of the coupling coefficient. This further affects the frequency splitting, in which the coil resonance apart from the operational frequency as demonstrated in [6]. This suggests that in order to have a higher power transfer efficiency, the transmitting and receiving coils have to be closed to each other and oriented accordingly. As an illustration, the improved wireless power transfer efficiency over a longer distance is presented by utilizing multiple repeaters and by changing the orientation of the coil [7]. Anyhow, the independent of the wireless power transfer efficiency on the resonance frequency is extended in details in [6]. The paper validated that the peak of power transfer efficiency for a different coupling coefficient occurs at a different so-called resonance frequency.

In general, the power transfer efficiency of the wireless power transfer can be improved either by 1) frequency tracking, 2) impedance matching. There are a lot of works which compensate the loosely coupled coils by capacitors to push the coils into resonance [8, 9, 10] and matching the receiving coil impedance with the load impedance [9, 11]. As an example, in [8], the set of variable capacitors are added to the loop on the power transmission side to adjust the matching. In this work, the addition of the capacitor is to set the input impedance of the transmission circuit equal to the impedance of the transmission coil, ensuring the power transfer efficiency at a maximum. While in [12], the serial/parallel capacitor matrix is added to the transmitter to reconfigure and track the optimum impedance-matching point dynamically. As described, the inductance of the coils thus the mutual inductance is changing by a distance changed. The changes in the inductance of the coil and mutual inductance have an effect in the input impedance of the transmission circuit. As in [8], the inclusion of the series/parallel capacitor matrix to the network corrects the input impedance of the transmission circuit. In [9], the closed loop technique the equivalent load impedance is controlled by controlling the transmitting current of the input side. This is achieved by updating the transmitting side with the present impedance of the receiving side via Bluetooth. While in [10], the monitoring system with a closed loop for fine-tuning the resonance frequency of the secondary coil circuit is proposed. The system scans the resonance frequency on the primary coil and measures the output power on the secondary coil looking for the optimal point. This procedure reduces problems of coupling factor variations with the positioning of the coils during the battery charging. In this work, the compensation capacitor is placed between the receiving coil and the load in parallel. It is demonstrated in [11] that the maximum power transfer efficiency can be achieved by changing the ac voltage at the transmitting side and measuring the differences of the output power by using the Maximum Power Point Tracking (MPPT) method. In [11, 13 & 14], the maximum power transfer efficiency is achieved by regulating the load impedance through the dc-to-dc converter.

In [15 & 16], the regulation of the load impedance is conducted by using the a perturb and observe (P&O) technique. The similar P&O technique is used in [13 & 15] to track the maximum power transfer efficiency.

Currently, the research in wireless power transfer is toward power efficiency and distance coverage. Fortunately, there are many techniques proposed to improve wireless power transfer efficiency. This paper reviews and observes the relationship of the load impedance to the power transfer efficiency of the series-to-series inductive resonant wireless power transfer (WPT) in much detail.

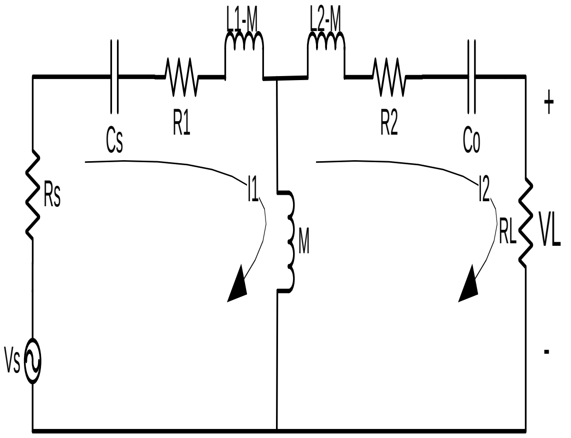

Figure 1: The series-to-series T-equivalent circuit

By referring to Figure 1, by assuming there are no losses in the capacitors and inductors then the power efficiency [1] of the series-to-series inductive resonant WPT can be expressed as

$$P_{eff} = \frac{\omega^2 M^2 R_L}{[(R_2+R_L)^2+{X_p}^2]R_1+\omega^2 M^2[R_2+R_L]} \quad \textbf{(1)}$$

Equation 1 is used extensively in analyzing the power transfer efficiency, throughout this paper.

Design of Experiment Setup

In all of the simulations conducted, the values of the source impedance (Rs), primary coil resistance (R1), secondary coil resistance (R2) is set to 1Ω. While the primary capacitance (Cs) and secondary capacitance (Co) is set to 1μF and the primary and secondary inductance is set to 10mH. The effect of load variation to the power transfer efficiency is first observed by observing the plot of power transfer efficiency of series-to-series inductive resonant WPT of 3 different load impedances against frequency. The coupling coefficient (k) is set to 0.01, 0.1, 0.2, …., 0.9 and 1.0, while the load impedance is set to 10Ω, 50Ω and 100Ω alternately. The corresponding graph of the power transfer efficiency is plotted in Fig. 2 to Fig. 4 and analyzed. This gives an insight idea of the variations of load impedance against the coupling coefficient and the power efficiency.

Further, the effect of load variation on the power transfer efficiency is studied in greater detail. The power efficiency for the set of the coupling coefficient (k) of 0.01, 0.1, 0.2, …., 0.9, & 1.0 is repeatedly calculated for load resistance of 1Ω, 10Ω to 80Ω in the step of 10Ω. For all the cases, the power transfer efficiency is calculated at the resonant frequency, at 1590Hz. The calculated power transfer efficiency with respect to the coupling coefficient (k) and the load impedance is copied into Table 1.

Whereas the optimum loads impedance is traced by swapping the frequency from 500Hz to 5000Hz in the step of 10Hz while swapping the load impedance from 1Ω to 200Ω in the step of 1Ω. The optimum load impedance is deduced by finding the highest corresponding power transfer efficiency using MATLAB ® find peak function. Finally, the optimum load resistance and the power transfer efficiency is copied in column 2 and column 3 of Table 2.

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2. Results and Discussions

The plot of the power efficiency with respect to the coupling coefficient (k) for load resistance of 10Ω, 50Ω and 100Ω was shown in Figure 2, Figure 3 and Figure 4 respectively. It is clear from the plots, that the maximum power transfer efficiency appearing at the resonant frequency for all values of the coupling coefficient (k). This meets the agreement that the maximum power transfer efficiency for series-to-series inductive wireless power transfer occurs at the resonant frequency of the receiving coil.

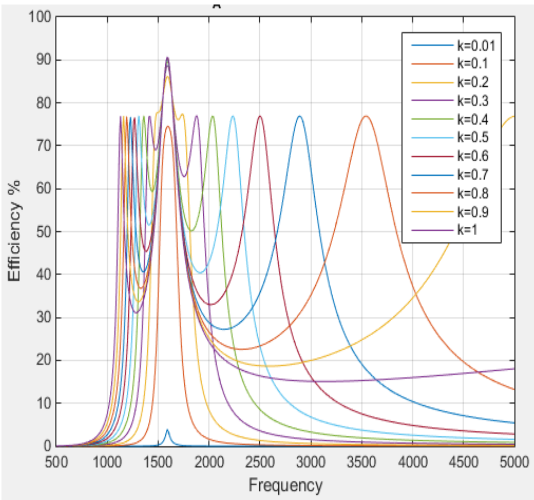

Figure 2: The graph of power transfer efficiency at load impedance of 10Ω

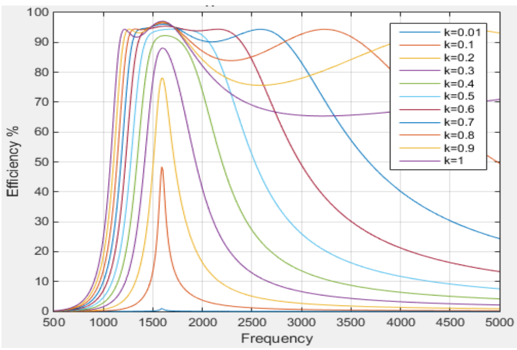

Figure 3: The graph of power transfer efficiency at load impedance of 50Ω

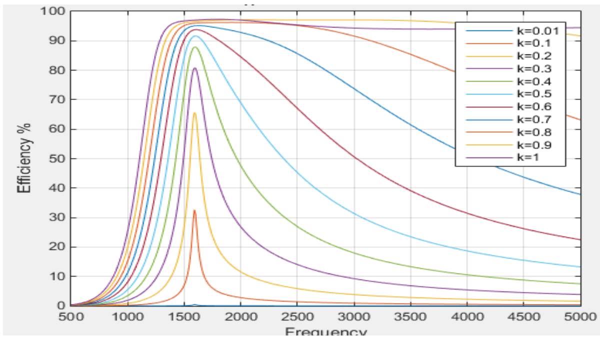

Figure 4: The graph of power transfer efficiency at load impedance of 100Ω

Further comparing the plots in Figure 2, Figure 3 and Figure 4, showing the smoother power transfer plot at higher load impedance such in Figure 4. In addition, by comparing the graph in Figure 2, Figure 3 and Figure 4; the lower load impedance gives the highest power transfer efficiency at the lower coupling coefficient. In contrast, the higher load impedance gives the highest power transfer efficiency at the higher coupling coefficient. This indicates that the load impedance governs power transfer efficiency. Further, the power transfer efficiency for load resistance of 10Ω to 80Ω in the step of 10 was calculated and tabulated in Table 1 for the set of the coupling coefficient (k) of 0.01, 0.1, 0.2, …., 0.9, & 1.0. The calculated power transfer efficiency with respect to the coupling coefficient (k) and the load resistance is listed in Table 1. By careful inspection of Table 1, it is clear that the optimum load resistance for the series-to-series inductive resonant WPT is in incremental trends by incrementing of the coupling coefficient. For example, the optimum load impedance for the coupling coefficient 0f 0.1 occurs within 10Ω to 20Ω. The highest power efficiency for each coupling coefficient (k) is denoted in red to ease the reader. The highest power efficiency listed in Table 1 is 82.03% when the load impedance is 20Ω.

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Table 1: The power transfer efficiency with respect to the coupling coefficient and load impedance

Coupling Coefficient (k)	Load impedance (Ω)								
	1	10	20	30	40	50	60	70	80
0.01	6.14	3.15	1.77	1.23	0.94	0.76	0.64	0.55	0.48
0.1	39.59	74.06	65.74	57.54	50.81	45.36	40.90	37.21	34.11
0.2	40.22	85.71	86.03	83.45	80.37	77.25	74.23	71.35	68.64
0.3	40.33	88.13	90.86	90.44	89.26	87.81	86.27	84.69	83.12
0.4	40.37	88.99	92.65	93.09	92.73	92.06	91.25	90.37	89.44
0.5	40.39	89.40	93.49	94.36	94.41	94.14	93.71	93.20	92.63
0.6	40.40	89.62	93.95	95.05	95.34	95.29	95.09	94.79	94.44
0.7	40.40	89.75	94.23	95.48	95.91	96.00	95.93	95.77	95.56
0.8	40.40	89.84	94.41	95.76	96.28	96.46	96.49	96.42	96.29
0.9	40.41	89.90	94.54	95.95	96.53	96.78	96.87	96.87	96.80
1.0	40.41	89.94	94.63	96.08	96.71	97.01	97.15	97.19	97.17
Average Efficiency	37.19	79.86	82.03	81.68	80.84	79.90	78.96	78.04	77.15

While in Table 2, the optimum load impedance for the set of the coupling coefficient (k) of 0.01, 0.1, 0.2, …, 0.9, and 0.99, were listed. It can be seen that the optimum load impedance is dynamically changed by the coupling coefficient. By comparing Table 1 and Table 2, it comes into a consensus that the optimum load resistance is incrementally increased by the increment of the coupling coefficient.

Table 2: Optimum load impedance and efficiency with respect to the coupling coefficient

Coupling Coefficien t (k)	Optimum load impedance	Efficiency
0.01	1.25	10.10
0.10	7	75.43
0.20	14	86.82
0.30	22	91.02
0.40	29	93.19
0.50	36	94.52
0.60	45	95.42
0.70	53	96.06
0.80	60	96.55
0.90	73	96.93
0.99	77	97.24

The graph of the optimum load impedance against the coupling coefficient is presented in Fig. 5. The graph shows almost linearly relationship between the optimum load impedance against the coupling coefficient. The linearity relation of the coupling coefficient and the optimum load impedance gives a way to predict either the optimum load impedance or the coupling coefficient by giving the one.

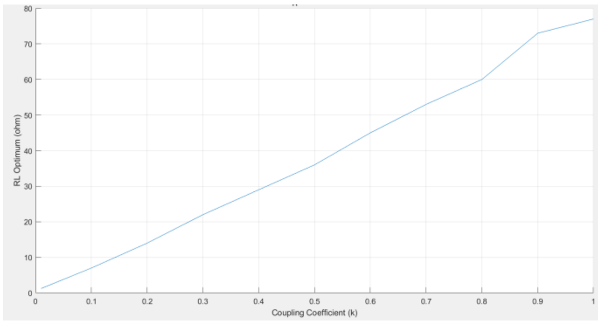

Figure 5: the graph of optimum load impedance against the coupling coefficient

By using the optimum load impedance in Table 2, the power efficiency for the set of the coupling coefficient (k) of 0.01, 0.1, 0.2, …., 0.9, and 0.99 is plotted as in Figure 6. The graph shows the improvement of power transfer efficiency which is clearly shown at the lower coupling coefficient. The average power transfer efficiency by employing the optimum load impedance is found to 84.84%. This is about 2.82% greater than the average power transfer efficiency when the load is 20 Ω.

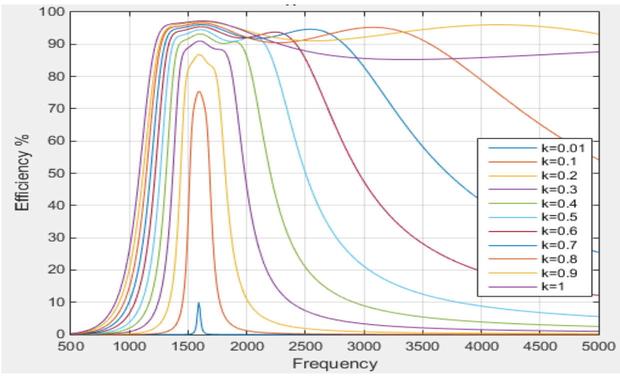

Figure 6: The plot of power transfer efficiency at the optimum load impedance

3. Conclusion

In general, the power transfer efficiency of the series-to-series inductive resonant WPT is depending on the coupling coefficient (k). It suggests that the higher the coupling coefficient, the higher the power transfer efficiency. In addition, the maximum power efficiency is found to be at the resonant frequency. However, the load impedance is also a factor in determining the power transfer efficiency. Referring to Table I, the optimum load impedance is diverging for different coupling coefficient. As an example, in Table 2 the optimum load impedance at the coupling coefficient of 0.2 is 14Ω, giving the power transfer efficiency of 86.82%, compared to the highest in the Table, 86.03% at 20Ω. While at a coupling coefficient of 0.5, the optimum load impedance is 36Ω, giving the power transfer efficiency of 94.52%. This is better than 94.41% at 40Ω. This concludes that the optimum load impedance gives a better power transfer efficiency. Anyhow, by referring to Table 2, the average power transfer efficiency by utilizing the optimum load impedance is 84.84% which is about 2.82% of average power transfer by fixing the load impedance to 20Ω. The 2.82% is a disregard for the low power transfer say 1W. But the 2.82% is considerable for the system to transfer say1Kw of power.

In addition, the optimum load impedance for different coupling coefficient suggests the inclusion of the 'matching impedance' network in between the receiving coil and the load. The Maximum Power Point Tracking algorithm such applied in photovoltaic power tracking possibly can be used in this area. With a bit modification on the algorithm, the MPPT could idealize the maximum power transfer for the series-to-series inductive resonant WPT. Therefore, the future focus will be in designing of the matching impedance network for the series-to-series inductive resonant WPT. In this area, the dc-to-dc converter in the matching the network impedance will be used and analyzed in detail. On top of it, some control techniques will be utilized.

As a conclusion, in order to maximize the power transfer efficiency of the series-to-series inductive resonant WPT, the operating frequency must be set at the resonance frequency and the 'matching impedance' network must be included in between the receiving coil and the load. The matching impedance network matches the impedance of coils with the impedance of the load, thus giving the power transfer at the maximum.

Acknowledgments

The technical support by colleagues and staff of the UniKL and IIUM are gratefully acknowledged. We also would like to thank the anonymous referees for valuable comments and suggestions. Financial assistance for this research by the IIUM Research Management Center (RMC) via RIGS Grant No RIGS 15-147-0147 and RMC RIGS 16-067-0231 are highly acknowledged.

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