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Parameter Trade-off between Electric Load, Quality Factor and Coupling Coefficient for Performance Enrichment of Wireless Power Transfer System

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Abstract—Accomplishing high efficiency with acceptable output load power is a formidable design challenge in resonant wireless power transfer (WPT) system employed for charging Electric Vehicle (EV). This necessitates a trade-off among the assorted parameters like coil quality factor, coupling coefficient, and electric load for performance enrichment of resonant WPT system. It is realized that the high value of quality factor does not ensure higher power transfer efficiency, but it is largely influenced by the electric load. For each coupling coefficient there exists an optimum load for which maximum power can be delivered. It is also perceived that for a fixed vertical separation gap of the coils, increasing receiver coil quality factor has no profound effect on the output load power as well as efficiency. The circuit model based analytical results agree well with the comprehensive experimental ones and elucidate the strategic design guidelines for a competent wireless electric vehicle charging system.

1. INTRODUCTION

Recent years have witnessed the wireless power transfer (WPT) being a viable future technology for powering or charging EVs. As a reliable, convenient and cordless power transfer method, inductive coupling based WPT system has been entailed in various applications starting from consumer electronic appliances to electric vehicles [1–5]. Despite the fact that inductive coupling based WPT system has been used for different applications, unfortunately, it could not mitigate the consumer needs due to its inefficiency and power delivery capability over a long range. Nevertheless, over the years the magnetic resonance coupling based WPT (MRC-WPT) systems have been proven providentially as a competent alternative [6–8]. It is well known that the performance of MRC-WPT system depends on different operating functional parameters like coil dimension, coil properties, quality factor of coils, physical spacing of coils, alignment of the coils, mutual coupling, frequency, electric load, etc. Indeed, the larger value of coupling coefficient and quality factor of the coils has profound effect to maximize the power transfer capability [9–12]. Moreover, WPT system operates at high frequency, and the high frequency current flow through the transmitter and receiver coil is not uniform because of the external magnetic field. As a result, the area of the coil wire exposed for conduction is much smaller than the cross section of the wire, and an excess frequency dependant resistance will be induced in the coil. Consequently, the quality factor of the coil which is supposed to be linearly frequency dependant now seems much more complex. Needless to say, at high frequency, there are two types of power loss in the coils: conductive and inductive losses. The conductive loss is usually related with the skin effect and DC resistance whereas the inductive loss results from the proximity effect. As a result, two types of resistance explicitly conductive and inductive resistances seem to be accompanied with the coils to

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imitate the losses [13–19]. Hence, this mutual inclusive assertion appeals a correlation which must be outlined. Therefore, in the present exploration, the correlation between the maximum power transfer ability and the quality factor of the coils as well as coupling coefficient under different electric load conditions has been delineated. The effectiveness of the proposed circuit model based power transfer characteristics has been validated through the experimental results. The obtained knowledge paves the way of design modus operandi through which an effective wireless charging system can be intended.

2. EQUIVALENT CIRCUIT MODEL

To understand the mechanism and realize the effect of running parameters on the performance of MRC-WPT system in the near field, reflected load theory (RLT) based circuit analysis is utilized here. It states that the current flow across the transmitter coil is regulated by the load which is present in the receiver coil. In this case, at the primary side, the same load does not appear with the same value of the load, but instead as a function of the mutual coupling between transmitter coil and receiver coil as well as the load value. The usual equivalent circuit of RIC-WPT system is depicted in Fig. 1(a). This circuit can be modified by using the equivalent model of lossy inductor which is illustrated in Fig. 1(b).

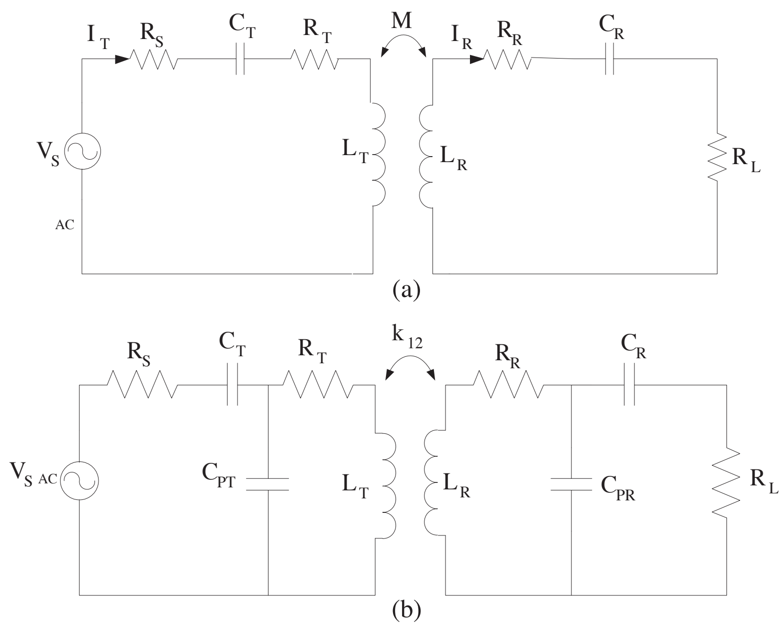

Figure 1. (a) Equivalent circuit of the RIC-WPT system. (b) Modified equivalent circuit.

The quality factors of transmitter and receiver coils are given by $Q_1 = \omega L_T/R_T$ and $Q_2 = \omega L_R/R_R$, respectively. In receiver side, the parasitic resistance of L_R can be equivalently converted to a shunt resistance equal to $R_{2P} = Q_2^2 R_R$, which is parallel with R_L. The equivalent capacitance C_{eq} is referred as $C_{eq} = C_{PR}||C_R$ where C_{PR} is the parallel connected parasitic capacitor, and C_R is the shunt equivalent of series capacitor. The combined resistance of R_{2P} and R_L is referred as $R_P = (R_{2P}||R_L)$. This modified equivalent circuit is given in Figs. 2(a) and (b). The total mutual inductance between the transmitter and receiver coils can be interpreted into equivalent reflected impedance $(L_{ref}, C_{ref}, R_{ref})$ on the transmitter side loop. Thus, the final equivalent circuit model of the MRC-WPT system using RLT is elucidated as the circuit given in Fig. 2(c). The reflected receiver impedance onto the transmitter side shown in the figure is given by:

$$R_{ref} = k_{12}^2 \left(\frac{L_T}{L_R}\right) R_P = k_{12}^2 \omega L_T Q_{2L} \tag{1}$$

$$_{ref} = \left(\frac{L_R}{L_T}\right)\left(\frac{C_{eq}}{k_{12}^2}\right) = \frac{1}{(\omega^2 L_T k_{12}^2)} \tag{2}$$

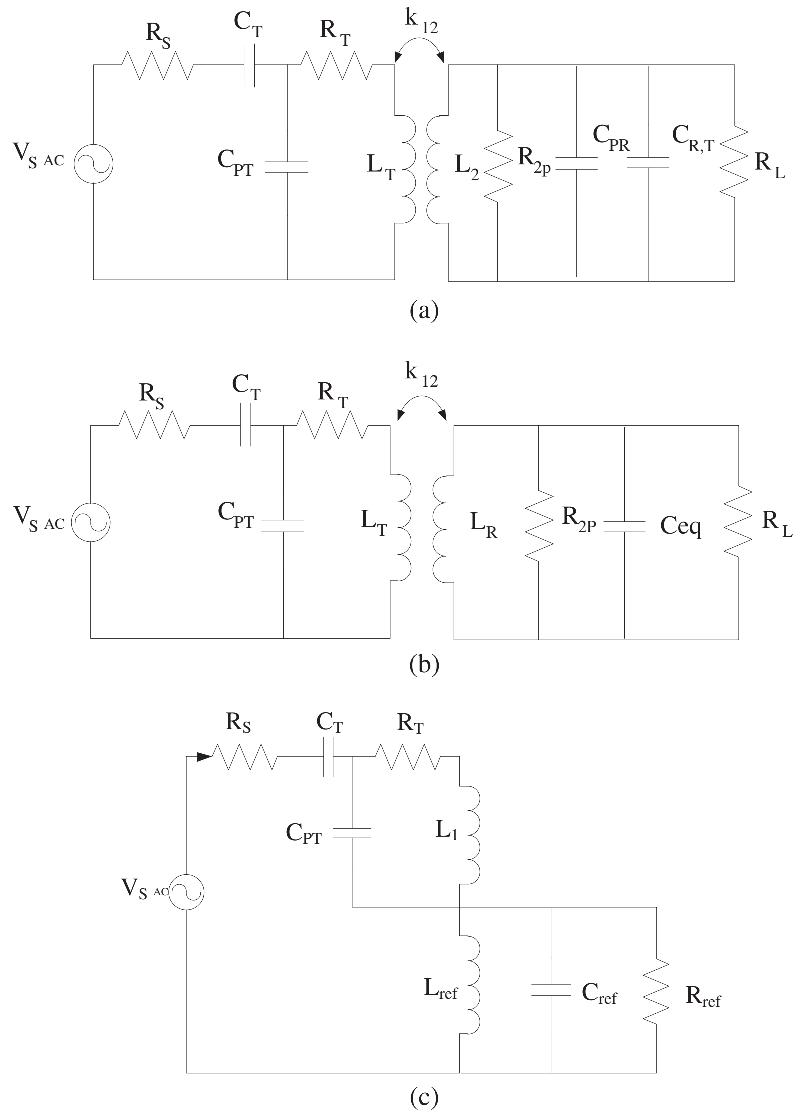

Figure 2. (a) (b) Modified equivalent circuit of RIC-WPT system. (c) Final equivalent circuit of RIC-WPT system using RLT.

where $Q_{2L} = R_P/\omega L_R$ is the quality factor of the receiver coil. When the circuit operates at the resonance frequency $\omega_0 = 1\big/\sqrt{L_1 C_1} = 1\big/\sqrt{L_2 C_2}$, the reactive parts cancel out and can be represented as a pure resistive circuit with components R_S, R_T, R_{ref} and $(R_1 = R_S + R_T)$ on the transmitter side.

The resonant inductive link model now behaves as a simple voltage divider circuit. Hence, the power transfer efficiency is calculated as follows:

$$\eta_{2\text{-}coil} = \frac{R_{ref}}{R_S + R_T + R_{ref}} \frac{R_{2P}}{R_{2P} + R_L} \tag{3}$$

Further, the power transfer efficiency (PTE) can be written as the function of coupling coefficient and quality factor as

$$\eta_{2\text{-}coil} = \frac{k_{12}^2 Q_1 Q_{2L}}{1 + k_{12}^2 Q_1 Q_{2L}} \left(\frac{Q_{2L}}{Q_L}\right) \tag{4}$$

Here, $Q_L = R_L/\omega L_R$ is known as the load quality factor and $Q_{2L} = Q_2 Q_L/(Q_2 + Q_L)$. The power delivered to load can be calculated as follows:

$$P_{2\text{-}coil} = \frac{V_S^2 R_{ref}}{2\left(R_S + R_T + R_{ref}\right)^2}\frac{Q_{2L}}{Q_L} = \frac{V_S^2}{2\left(R_S + R_T + R_{ref}\right)}\frac{k_{12}^2 Q_1 Q_{2L}}{1 + k_{12}^2 Q_1 Q_{2L}}\frac{Q_{2L}}{Q_L} \tag{5}$$

It is well known from the maximum power transfer theorem that the maximum power will be delivered to the load when the reflected impedance from the receiver coil matches the primary coil impedance. So, the optimum value of R_{ref} for which maximum power is delivered to the load (PDL) can be calculated by

$$\frac{dP_{2\text{-}coil}}{dR_{ref}} = 0$$

Again, under this condition, it is clear that PTE is well below 50% as maximum PTE and PDL cannot be simultaneously achieved with a given set of parameters. Thus for a certain value of load impedance and coil quality factor, there exist an optimal coupling coefficient to ensure the PDL maximum.

This indicates that there is a need of trade-off between the PTE and PDL. According to the different criteria and conditions, optimal parameters should be defined and designed. Furthermore, from the above Equations (4) and (5), it can be noticed that both the PTE and PDL are the function of coupling coefficient and the quality factor of the coils. Here, Q is affected by the wire properties and coil radius, whereas the coupling coefficient is dependent on the size of the coils and the distance between the coils. In order to maximize the PTE, large values of k_{12}, Q_1, and Q_2 are needed. In this case, PTE of the system can be maximized for an optimal load $R_{L,PTE} = \omega L_T Q_{LPTE}$ and a given set of k_{12}, Q_1, and Q_2 values. The maximum value of $Q_{L,PTE}$ can be calculated by taking the derivative of η_{12} w.r.t Q_L, which is given by

$$Q_{L,PTE} = \frac{Q_3}{\left(1 + k_{12}^2 Q_1 Q_2\right)^{1/2}} \tag{6}$$

The presented analysis reveals that both PTE and PDL are sensitive to the quality factor of the coils and coupling coefficient depending on the electric load conditions.

3. ANALYTICAL AND EXPERIMENTAL RESULTS

In order to substantiate the analytical results with experimental results, a practical MRC-WPT system has been designed whose photograph is illustrated in Fig. 3. High frequency energy is supplied from the Function Generator (Model FG1MD, 1 MHz) to the transmitting coil through a high efficiency power amplifier (DC-10 MHz/50 VA HSA 4101). The transmitting and receiving coils are mutually coupled to each other and resonate to a particular frequency 22.2 kHz through externally connected capacitors. The experimental results are visualized and analyzed with the help of a dual-channel Digital Storage Oscilloscope (36025D, 25 MHz, 100 MS/s). The electric load is connected to the receiving coil and

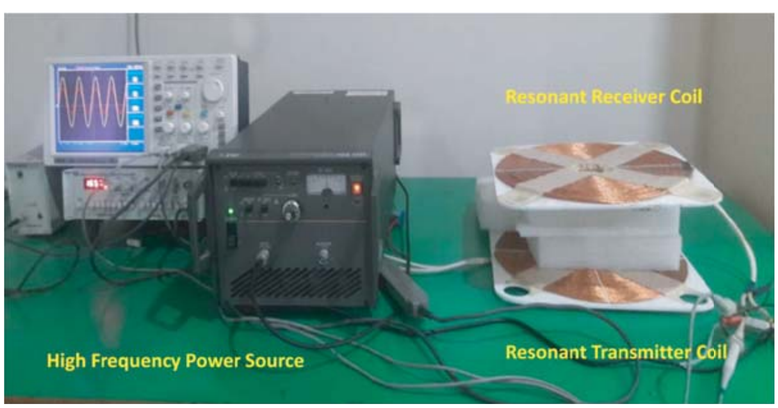

Figure 3. Practical demonstration of MRC based WPT System.

varied to cover a wide range of application from high performance EV to sophisticate implants. By the principle, high frequencies AC excited mutually coupled coils enable the wireless power transfer through the resonant magnetic field between the coils. As a result, electric power is transferred wirelessly from transmitting to receiving coils. Both the transmitting and receiving coils are spirally configured with 32 turns each and made up of Litz copper wire (AWG32). The inner and outer radii of both the coils are 2 cm and 15 cm, respectively, and the pitch has been kept as 0.25 mm. Instead of using different sets of transmitting coil to vary the quality factor and coupling coefficient, a single transmitting coil with different tapping points is selected.

The practical values of different parameters used for experimental validation of the analytical results are given in Table 1.

Table 1. Practical values of design parameters.

Input AC voltage (V_P)	4.12 V
Primary Coil Inductance (L_P)	168 µH
Secondary Coil Inductance (L_S)	168 µH
Primary Tuning Capacitance (C_P)	330 nF
Secondary Tuning Capacitance (C_S)	330 nF
Effective Series Resistance (ESR) of Primary coil (R_P)	192 mΩ
Effective Series Resistance (ESR) of Secondary coil (R_S)	192 mΩ
Operating Resonant Frequency (f_0)	22.2 kHz

The observed analytical power transfer efficiency characteristics with Q-factors of the receiver coil and coupling coefficient are depicted in Fig. 4(a), and their experimental characteristics are illustrated in Figs. 4(b) and 4(c). The experimental and analytical results disclose that the PTE characteristics are affected not only by the coupling coefficient but also by the Q-factor of the receiver coil. It is evident from the illustrated result that from a particular value of Q-factor of the receiver coil, the PTE increases gradually with increase in coupling coefficient. At a specific coupling coefficient, the PTE attains the maximum whereas for very low values of receiver coil quality factor it declines. These results signify that the quality factor of receiver coil should be at least above the critical value which will be taken into account for designing an effective WPT system for EVs. A similar nature has been realized from the elucidated experimental PTE characteristics of the coupling coefficient between the coils and Q-factor of the receiver coil. The PTE characteristics corresponding to the coil quality factor imply that there is no such an intense effect on PTE after a certain value of quality factor of the receiver coil. It is well known that Q-factor of the coil is affected by the wire property and coil dimension. Nevertheless, it is practically difficult to adjust the coupling coefficient (as it is usually a non-tuneable parameter and generally depends on the coil geometry, separation gap, and alignment of coils) rather than quality factor of the receiver coil. This clearly suggests that the coupling coefficient and Q-factor should be considered simultaneously for designing an effective WPT system.

The electric load characteristics of PTE with respect to the coupling coefficient and Q-factor of the receiver coil are provided in Figs. 5(a) and 5(b). It is noticed that the high value of coil quality factor does not ensure higher power transfer efficiency, but it is largely influenced by the electric load. Thus to build up an effective WPT system, the quality factor and load resistance of the receiver coil have to be taken into account simultaneously.

In order to analyze the dependence of output load power on the Q-factor of receiver coils, coupling coefficient, and load resistance, the analysis has been carried out, and their characteristics are shown in Figs. 6(a)–(c). From the result it is clear that there exists a narrow region of coupling coefficient corresponding to different values of quality factor for maximum power to be delivered. Again, with the designed constraint to achieve a higher coupling coefficient for a given set of parameters it is quite positive to accomplish the desired power delivery capabilities at lower value of coupling coefficient. It is realized that for each coupling coefficient there exists an optimal electric load for which maximum

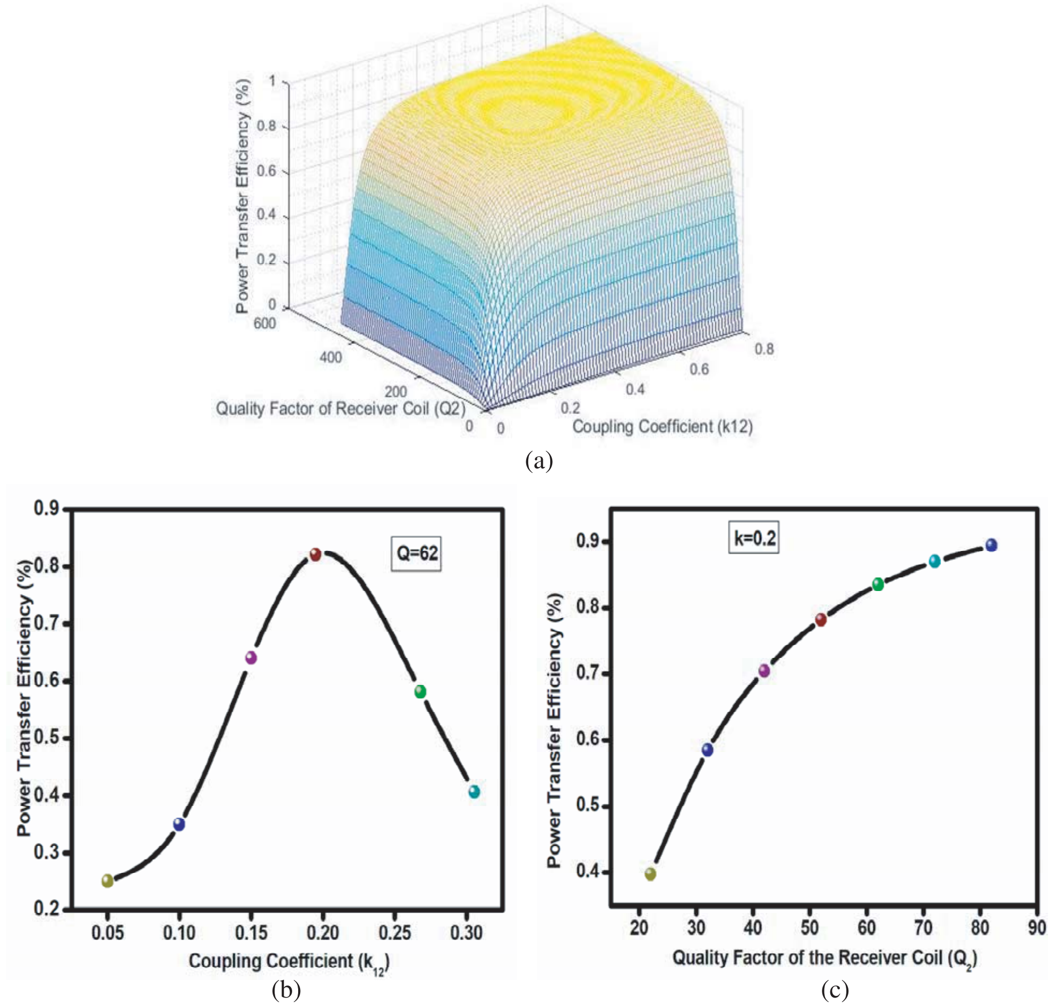

Figure 4. (a) Theoretical power transfer efficiency characteristics vs quality factor of the receiver coils and coupling coefficient. (b) Experimental dependence of coupling coefficient on the power transfer efficiency. (c) Experimental dependence of quality factor of the receiver coil on the power transfer efficiency.

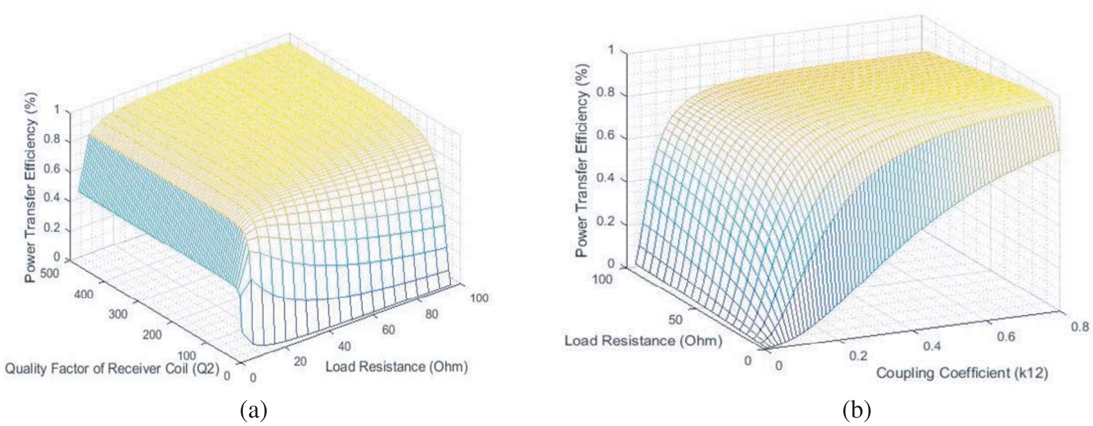

Figure 5. (a) PTE vs quality factor and coupling coefficient. (b) PTE vs quality factor and load.

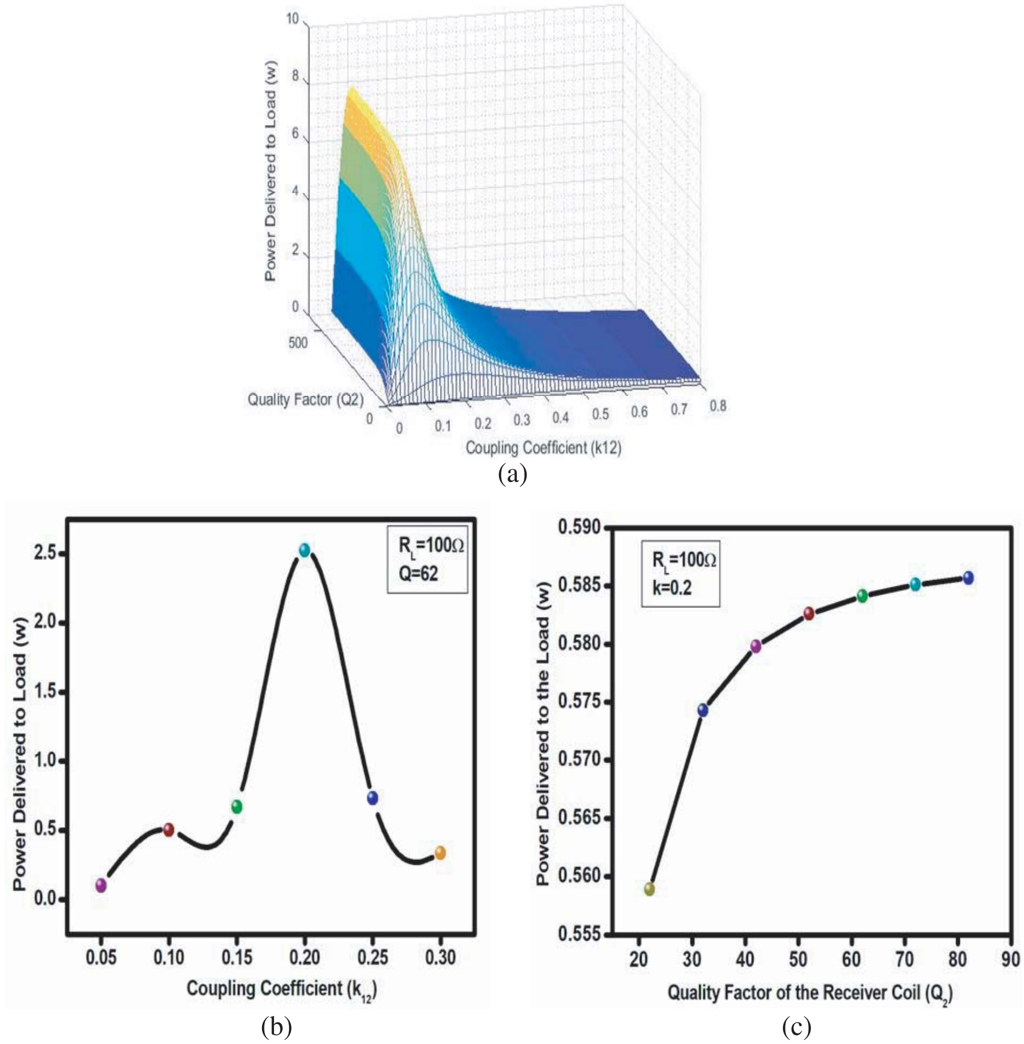

Figure 6. (a) Theoretical Output load power characteristics vs quality factor of the receiver coils and coupling coefficient. (b) Experimental dependence of coupling coefficient on the power delivered to load. (c) Experimental dependence of quality factor on the power delivered to load.

power can be delivered to the WPT system. It reveals that for maximum output load power at the receiver side, the main key factor is the tighter coupling between the coils. Also, it is observed that for a fixed coupling coefficient (fixed vertical separation gap) of the coils, increase on Q-factor of the receiver coil has no profound effect on the output load power. It is evident from Fig. 6(c) that neither individual increment of receiver quality factor nor coupling coefficient ensures the maximum power transfer to the load. However, careful selection of the dependant parameter ascertains the optimal power transfer to the load; hence a trade-off between these parameters is inevitable.

The observed analytical output load power characteristics with the coupling coefficient and electric load are depicted in Figs. 7(a)–(b), and their experimental characteristic is illustrated in Fig. 7(c). These results indicate that the output load power characteristics are affected not only by the coupling coefficient but also by the Q-factor of the receiver coil under different electric load conditions. The interesting fact from the result given in Fig. 7(b) is that maximum power can still be delivered to the load with smaller electric load value at a lower value of coupling coefficient corresponding to a reasonable quality factor of the receiving coil which is feasible within the system designed constraint. However, it has been indicated in Fig. 7(a) that the power transfer to the load attains maximum at higher value of coupling coefficient, which practically may not be achievable with the given set of design parameters.

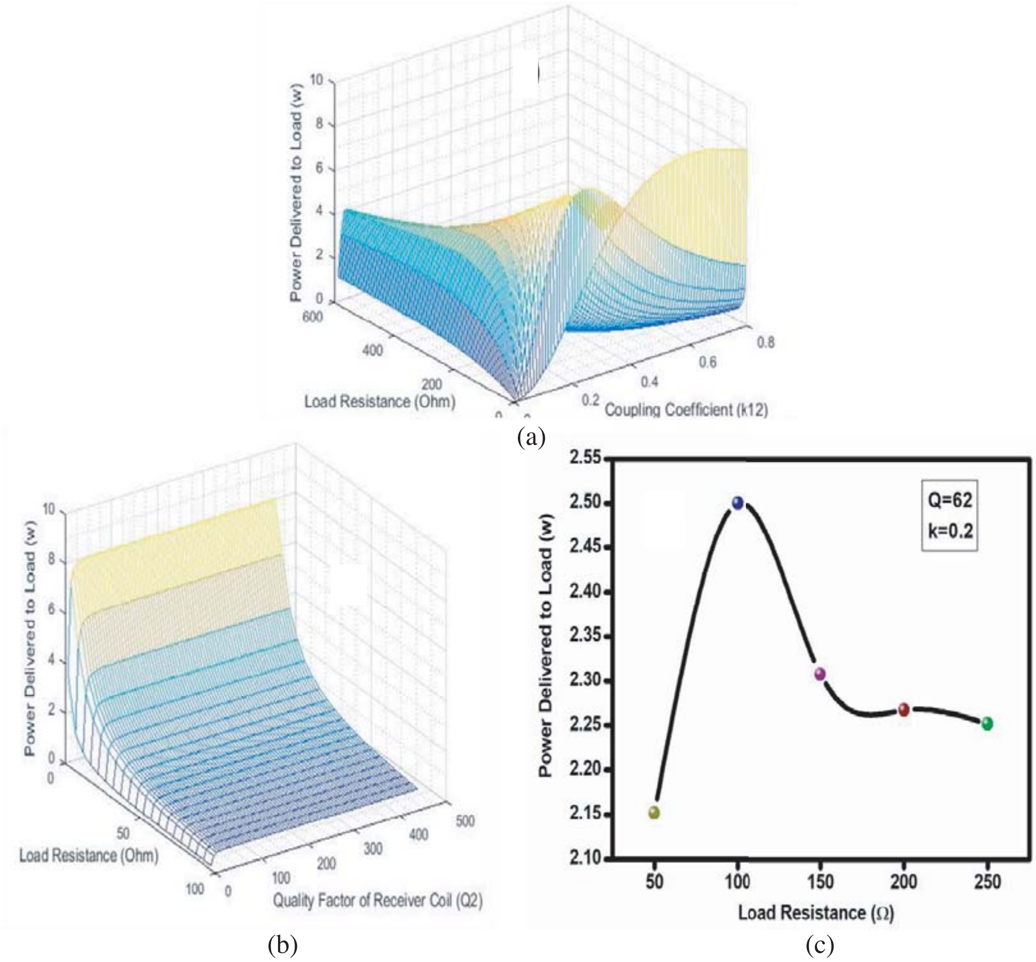

Figure 7. (a) Theoretical output load power characteristics vs coupling coefficient and load resistance. (b) Theoretical output load power characteristics vs quality factor of the receiver coils and load resistance. (c) Experimental dependence of electric load resistance on the output power.

For a certain electric load resistance corresponding to a coupling coefficient, the load power reaches its peak value whereas for lower values of coupling coefficient there is no such intense effect with the increase in electric load. It clearly reflects that the quality factor has a major role in enriching the power transfer capability at that coupling coefficient, which has been signified from the result illustrated in Fig. 7(b). From the experimental characteristics, it can be seen that there exists an optimal electric load corresponding to a fixed quality factor and coupling coefficient in order to retain the maximum power transfer. Therefore, it is utmostly required to decide the coupling coefficient and quality factor of the coil under different electric load conditions to enhance the power transfer capability for a competent wireless electric vehicle charging system.

4. CONCLUSION

To instigate the parameter trade-off among electric load, quality factor, and coupling coefficient for performance enrichment of a wireless power transfer system, a theoretical equivalent circuit model has been developed, and the obtained results are substantiated through experimentally measured results. From the observed results, it can be predicted that both the power transfer efficiency and power delivered to load depend on the quality factor of the coils, coupling coefficient, and electric load. The quality factor is affected by the radius of the coil and wire properties, whereas the coupling coefficient between the coils is dependent on the coil sizes and the separation distance. Thus to design an effective WPT system for EV charging, the quality factor of the coils and coupling coefficient have to be taken into consideration simultaneously depending on the electric load conditions.

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