Investigation of correlation of design parameters in wireless power transfer system

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Abstract
Achieving higher power transfer efficiency with permissible output load power is a formidable challenge in designing a magnetically coupled resonant wireless power transfer system. Consequently, to instigate the power transfer characteristics, the theoretical models based on reflected load theory as well as lumped circuit models have been employed, which have been substantiated with the experimental measurements. It has been apprehended that maximum efficiency as well as the power delivered to the load can be enriched from the depreciated value through appropriate deliberation of coil’s quality factor (coil design dependent) and coupling coefficient with acceptable operating frequency under different electric load conditions. The obtained results illuminate the correlation between the maximum power transfer ability and the quality factor of the coils, as well as the coupling coefficient, under different electric load conditions.

1 INTRODUCTION

Wireless power transfer system (WPTS) by means of an electromagnetic field without any carrier medium for powering electrical and electronic devices is exerting a pull on both industrial and scientific research communities [1]. Recently, commercialisation of the emerging wireless power transfer (WPT) technology is in the spotlight owing to its diversified application range such as smart electrical/electronic gadgets, industrial facilities, medical implants and electric vehicles [2–8]. Nevertheless, as an advancement, foreign metallic object detection technology nowadays is getting much attention in the WPT industry specifically in consumer electronics application like wireless charging pad [9]. In addition, to make weather independent as well as to nullify the demand of powering more distributed sensors for online monitoring the power transmission and distribution, domino WPT systems are currently used on the High voltage (HV) transmission lines [10]. The initiative of wireless powering especially through magnetic resonance coupling has recently been fetched to the front because of its convenience, simplicity, cordless, efficient, reliable and safe method for all weather conditions [11–13]. But, in order to put up a viable power transfer system, it is not good enough to present the power being transferred from the source side to the receiver side of the device through a resonant inductive link. It is primarily required to concentrate on the basic impediment, which grips the promise for futuristic WPTS. This urges the development of theoretical models to realise the operating mechanism and the influence of functioning parameters on WPTS. Although WPTS has been practically developed and the effect of frequency, coupling coefficient, coil quality factor and electric load on its performance have been identified, maximum power transfer efficiency (PTE) and power delivered to load (PDL) cannot be achieved simultaneously with a given set of parameters. This research pursuit necessitates the investigation of a correlation of design parameters in WPTS, that is, the correlation between the maximum power transfer ability and the quality factor of the coils, as well as as coupling coefficient, under different electric load conditions.

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2 | REFLECTED LOAD-BASED CIRCUIT MODEL ANALYSIS

2.1 | Equivalent circuit model

The usual magnetic resonant coupling-based WPTS involves two mutually coupled transmitter and receiver coils driven by a voltage source. The equivalent circuit of the series resonant WPTS is illustrated in Figure 1.

In order to visualise the power transfer method and assess the performance, a reflected load-based circuit theory approach has been adopted [14–16]. This approach presumes that the current across the transmitting coil is influenced by the electric load allied with receiving coil. This electric load does not appear to the transmitting coil with the same value of the load, but instead as a function of the load value and the mutual coupling between the transmitter and receiver coils. The total mutual inductance between the coils (transmitting and receiving coils) can be interpreted by applying reflected load theory (RLT) into equivalent reflected impedance ($L_{refL}$, $C_{refL}$, $R_{refL}$) on the transmitting-side loop of WPTS. Thus, by considering the resonant inductive link as a simple voltage divider circuit, the deduced modified equivalent circuit of resonant WPTS based on RLT is illustrated as the circuit given in Figure 2.

The PTE of the resonant inductive link can be calculated as follows [17]:

$$\eta_{2-coil} = \frac{R_{refL}}{R + R_{refL}} \frac{R_{p}}{R_{p} + R_{refL}}$$  \hspace{1cm} (1)

where

$$R_{refL} = k^2_{tr} \left( \frac{L_{r}}{L_{t}} \right) R_{p} = k^2_{tr} \frac{\omega L_{r} Q_{r}}{Q_{t}}.$$  \hspace{1cm} (2)

$$C_{refL} = \frac{L_{r}}{k^2_{tr} L_{t}} \frac{C_{eq}}{k^2_{tr} L_{t}} = \frac{1}{(\omega^2 L_{t} k^2_{tr})}.$$  \hspace{1cm} (3)

$$I_{refL} = k^2_{tr} L_{r}.$$  \hspace{1cm} (4)

The above PTE expression can be presented in terms of coupling coefficient and quality factor of the coils as

$$\eta_{2-coil} = \frac{k^2_{tr} Q_{r} Q_{t}}{1 + k^2_{tr} Q_{r} Q_{t}} \left( \frac{Q_{r}}{Q_{t}} \right)$$  \hspace{1cm} (5)

Hence, the power delivered to the load is

$$P_{2-coil} = \frac{V^2}{2(\sum R_{refL} + R_{refL})} \frac{Q_{r}}{Q_{t}} = \frac{V^2}{2(\sum R_{refL} + R_{refL})} \frac{k^2_{tr} Q_{r} Q_{t}}{1 + k^2_{tr} Q_{r} Q_{t}} \left( \frac{Q_{r}}{Q_{t}} \right)$$  \hspace{1cm} (6)

For maximum PDL:

$$\frac{dP_{2-coil}}{dR_{refL}} = 0$$  \hspace{1cm} (7)

It is realised that for a particular value of load impedance along with the coil’s quality factor, there is an optimal coupling efficient to make sure the PDL is maximum. This necessitates a trade-off between PDL and PTE.

It is also noticed that PDL and PTE both are a function of the coil’s quality factor and coupling coefficient, and both parameters are influenced by coil configuration, physical air gap, and the coil’s wire material properties.

To maximise efficiency for an optimal load $R_{L,PTE} = \omega L_{r} Q_{r} P_{L,PTE}$, large values of $Q_{r}$, $Q_{t}$ and $k_{tr}$ are required. So

$$Q_{L,PTE} = \frac{Q_{r}}{(1 + k^2_{tr} Q_{r} Q_{t})^2}$$  \hspace{1cm} (8)

This RLT-based electrical circuit model analysis discloses that both PDL and PTE are influenced by the coupling coefficient and coil’s quality factor depending on electric load.

2.2 | Results and discussion

A flow chart is illustrated in Figure 3 to delineate the correlation between the maximum power transfer ability and the quality factor of the coils, as well as the coupling coefficient, under different electric load conditions.

The PTE characteristics with respect to the receiver coil’s quality and coupling coefficient are illustrated in Figures 4 and 5.

It can be seen that from a particular value of $Q$ of the receiver coil, the PTE increases gradually with an increase in coupling coefficient, whereas it decreases for very low values of receiver coil quality factor. Hence, the receiver quality factor should be
Start

Check the dependence of coupling coefficient ($k$), quality factor of the coils ($Q$), electric load ($R_L$) on maximum power transfer with acceptable frequency of operation

Calculate the power transfer efficiency and load power using the reflected circuit theory and lumped circuit model based equations varying the design parameters such as $k$, $Q$ and $R_L$

Is power transfer maximum?

No

Yes

Determine the values of $k$, $Q$ and $R_L$ for which maximum power transfer efficiency as well power delivered to load achieved

Outline the correlation between the maximum power transfer ability and the coupling coefficient ($k$) as well as quality factor of the coils ($Q$) under different electric load conditions

End

FIGURE 3  Flowchart of the process involved

FIGURE 4  Power transfer efficiency (PTE) characteristics corresponding to the coupling coefficient and receiver coil's quality factor

FIGURE 5  PTE characteristics corresponding to electric load resistance and receiver coil's quality factor

FIGURE 6  PTE characteristics corresponding to electric load resistance and coupling coefficient

at least above the critical value. It suggests that it is vital to consider the receiver coil quality factor for designing an efficient WPTS for charging Electric Vehicles (EVs). The electric load-dependent PTE characteristics are shown in Figure 6. It has been comprehended that the elevated value of coil’s quality factor does not guarantee higher PTE, but it is considerably affected by the electric load. Thus, to design an efficient WPTS, both parameters (such as electric load and receiver coil’s quality factor) have to be taken into account concurrently.

Further analysis has been done to disclose the influence of parameters (such as coupling coefficient, coil’s quality factor and electric load) on the power delivery capability of WPTS. The PTE characteristics are illustrated in Figures 7(a)–(c). From the dependence of the coupling coefficient on output load power, it is noticed that the tighter coupling among the transmitting and receiving coils entails maximum output power across the receiver section, which is the key factor. It indicates the existence of an optimal load corresponding to each coupling coefficient for which PDL is maximum. Apart from this, with the design restraint to accomplish high coupling coefficient, it is rather possible to acquire the desired PDL at low value of coupling coefficient. It has been realised that neither increase of the coupling coefficient nor the coil’s quality factor warrants maximum PDL. Hence, the combination of design parameters should be appropriately selected so as to establish maximum power delivery of WPTS for charging EVs. From the electrical load characteristics it has been predicted that the output
power arrives at its peak for a particular coupling coefficient, while in lower coupling coefficient, there is no profound effect on PDL with the increment of load resistance. Thus, this analysis proposes the guideline to decide the appropriate value of coil’s quality factor and coupling coefficient under different load conditions to uphold the utmost power transfer.

3 | EXPERIMENTAL VALIDATION

In order to validate the power transfer characteristics results acquired from the analysis of the reflected load-based equivalent circuit model with the measured results, an experimental setup of WPTS has been built. The practical setup photograph is shown in Figure 8. The practical values of different parameters used for experimental setup of WPTS to carry out the measurements are given in Table 1.

The experimental PTE characteristics as a function of the coupling coefficient between the coils and receiver coil’s quality factor at optimum electric load and resonant frequency are illustrated in Figures 9(a) and (b). Similar trend has been noticed as observed through analytical equivalent circuit models. The experimental results well agree with analytical results. The experimental PTE characteristics clearly signify that there is no such intense effect on efficiency for higher value of coupling coefficient and after a particular value of receiver coil quality factor.

The experimental output load power (PDL) characteristics as a function of the receiver coil’s quality factor and its dependence on the electrical load allied with the receiver part are illustrated in Figures 10(a) and (b). The electrical load characteristic states that for an optimum load, the PDL attains its maximum. The quality factor characteristic hints that the power delivery performance can be enhanced with elevated value for coil’s quality factor. It explicates the strong coupling regime corresponding to the receiver coil’s quality factor and electric load resistance maximum efficiency and output load power. The experimental results have been substantiated with the analytical results, which recommend that that the coil’s quality factor and magnetic
coupling coefficient corresponding to physical air gap should be taken into account simultaneously for an effectual WPTS under different electric load conditions at resonance.

From the derived mathematical expressions that is supported by the simulation as well as experimental results, it can be articulated that for a particular value of load impedance along with coil’s quality factor, there is an optimal coupling coefficient to make sure the PDL is maximum. This necessitates the trade-off between PDL and PTE. However, from the design strategic point of view, this analysis provides the inherent correlation between the vital parameters like coupling coefficient, electric load resistance, coil’s quality factor and driving frequency and the influence of these on the system performance indicator like PTE and load power. Further, this correlation offers the design strategy, which is not design-specific, rather valid for a wide range of parameters variation. As an example, from Figures 9(a) and (b) and 10(a) and (b), the parameters combination of receiving coil quality factor $Q = 110$ for coupling coefficient $k = 0.23$ needs to be selected when the resistive load is $R_L = 100$ at the operating resonant frequency to uphold the maximum PTE as well as the load power.

4 | LUMPED CIRCUIT-BASED CIRCUIT MODEL

4.1 | Equivalent circuit model

To instigate the power transfer characteristics, the theoretical model based on the lumped circuit model has been employed. The equivalent circuit model is shown in Figure 11.
The output load power can be calculated by connecting the reflected receiver side impedance $Z_r$ in series to the transmitter side, assuming the source voltage $V_s$ is constant, and $I_t$ is allowed to vary with load value. The power transferred to the receiver side is calculated as $|I_t|^2 Z_r$. Hence, the output load power is [17]:

$$P_L = \frac{V_s^2 \omega_0^2 M^2 R_L}{R_p^2 (R_t + R_L)^2 + \omega_0^4 M^4 + 2 \omega_0^2 M^2 R_p (R_t + R_L)}$$

where

$$I_t = \frac{V_p}{R_t + \frac{\omega_0^2 M^2}{R_r + R_L}}$$

$$Z_r = \frac{\omega_0^2 M^2}{R_t + R_L + \omega L_r + \frac{1}{\omega C_r}}$$

If the system is operated at the resonance frequency ($\omega = \omega_0$), then the $Z_r$ is purely resistive and is given by

$$Z_r = \frac{\omega_0^2 M^2}{(R_t + R_L)}$$

It has been seen that from the above theoretical analysis, the load power is a function of resonant frequency, mutual inductance, load resistance and secondary coil resistance. It is understandable that for a fixed coil design, the effective resistance of the coil remains invariant.

At the resonant frequency, the PTE can be calculated as follows:

$$\eta_{2-coil,SS} = \frac{I_t^2 R_L}{I_r^2 (R_t + R_r)}$$

where

$$\frac{|I_t|}{I_r} = \frac{\omega_0 M}{R_t + R_L}$$

Thus,

$$\eta_{2-coil,SS} = \frac{R_L}{(R_t + R_L) \left(1 + \frac{R_t R_r + R_t R_L}{\omega_0^2 M^2}\right)}$$

From the above equation, it can be analysed that the efficiency merely depends on the impedance matching. Also, it can be noted that if the effective resistance of the receiver coil approaches zero, maximum efficiency tends to 100%. Therefore, for designing the coil, the wire resistance should be maintained as minimum as possible.

4.2 Results and discussion

The load power characteristic as a function of load resistance, coupling coefficient and frequency is illustrated in Figures 12(a)–(c).
It is seen that for a particular frequency, the output load power attains its maximum value for a particular load resistance corresponding to its coupling coefficient. As the coupling coefficient increases, the maximum output load power occurs with a shift in higher load resistance. It can also be seen that for fixed load, there exists an optimum frequency corresponding to the coupling coefficient for which output load power attains its maximum. For design consideration, load value and the operating frequency should be selected accordingly in order to maintain maximum output power.

5 CONCLUSION

There is a delusion that a higher coupling coefficient and higher quality factor between the transmitting and receiving coils is a doable condition for maximum WPT. But providentially it is explored that there exists a correlation between the maximum power transfer ability and the quality factor of the coils, as well as coupling coefficient, under different electric load conditions.

In the present exploration, the power transfer characteristics have been analysed using reflected load circuit theory and the lumped circuit model. The obtained power transfer characteristics have been validated through the experimentally measured results. The analysis based on RLT reveals that maximum efficiency as well as power delivered to the load can be enriched from the depreciated value through appropriate deliberation of coil’s quality factor and coupling coefficient with acceptable operating frequency under different electric load conditions.

The analysis using the lumped circuit model unveils that the PTE of the resonant inductive link merely depends not only on the design parameters but also on the impedance matching. Thus, to design an effective WPT system, the quality factor of the coils, electric loads coupling coefficient and impedance matching has to be taken into consideration simultaneously. The presented systematic analysis provides a correlation among the design parameters enabling maximum WPT.

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