A design method for developing a high misalignment tolerant wireless charging system for electric vehicles

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ABSTRACT

This paper proposes a design procedure which optimizes the electrical parameters involved in the Inductively Coupled Power Transfer (ICPT) system and correlates them with geometrical dimensions of the charging coils involved for charging of electric vehicles. The Inductively Coupled Power Transfer (ICPT) system makes it possible to charge the Electric Vehicles (EVs) wirelessly at some distance to avoid safety issues and to provide convenience to the users. The ICPT system has potential applications in the field of medical sciences, office appliances, industrial loading machines, and battery charging applications. Although the ICPT system has been successful for the charging of the electric vehicles, but it retains some challenges, prominently limitation of misalignment tolerance and low efficiency of the overall circuit. The methodology presented in this paper helps in choosing appropriate dimension of the coils and electrical parameters to cope with the issue of misalignment tolerance. A program based on the mathematical model has been developed in Matlab software to determine optimal values of overall ICPT system circuit parameters and the geometrical dimensions of coils. The experiments of the ICPT system have been carried out with developed optimal coil design for 1 kW power transfer at various air gaps. The misalignment tolerance of the ICPT system has been recorded and presented in the paper. The proposed optimal design achieves maximum efficiency of 90.5% at perfect alignment, however, it maintains efficiency of 72% at 35–40% misalignment between the coils. The misalignment test results support the design of coils for EV charging application.

1. Introduction

The fossil fuels are being consumed in huge quantity for electric power generation and transportation purposes [1]. However, the scarcity of the fossil fuels and emission of greenhouse gas emissions have encouraged the acceptance of electric vehicles (EVs) worldwide [2,3]. The EVs have provoked as a replacement for the conventional and pollutant transportation system [4–6]. Research in this emerging technology has been carried for last three decades [2,7–16].

The era of EVs has started and the EVs are growing very fast due to the convenience provided by them and other several advantages. In future, it seems these will replace completely the conventional transportation system [17,18]. The EVs can be powered over a longer air gap through wireless charging. This charging process is not affected by harsh weather conditions, as no plugins are required for the operation of wireless charging [19]. Although the EVs do not affect the environment directly, however, they affect relatively less than the conventional vehicles but these are being powered from the electric utility [20,21]. Thus, somehow, the EVs affect environment indirectly depending on the fuel of power generating station. The EVs offer less emanation of glasshouse fumes [22]. These are suitable for bi-directional power transfer when connected with a smart house system [23]. Inductively coupled power transfer (ICPT) has been a most successful method in consideration for the wireless charging of EV. Due to reasonable electrical isolation between transmitting coil and receiving coil, the ICPT system has the ability to operate in grimy conditions [24,25]. The ICPT system has been applied in many application i.e. electric vehicles, wireless sensor networks, robots, LED TV and medical implants etc. [26]. Despite aforementioned advantages, the limited mileage, less misalignment toleration, the efficiency of the complete ICPT system and the overall cost involved are still limitations [27–31]. Extensive research over the span of time, in different technical aspects i.e. magnetic designs of coils, LC compensation topologies, control of the system, optimization of system parameters and coil dimensions, has improved the performance of ICPT system [4,32–34]. However, these issues
require special consideration for the successful implementation of an electric powered driven vehicle system worldwide. The high misalignment tolerance and efficient power transfer are the main requirements for EV commercialization. The optimization of ICPT system parameters and coil dimensions can be employed for analysis and attain high efficiency and greater misalignment tolerance [6,22,35].

The main objective of this paper is to increase the misalignment tolerance of the coils. The behavior of the ICPT system based on optimized design parameters of the ICPT system has been presented in the paper. The experimental setup exhibits the maximum efficiency 90.5%.

Misalignment tolerance during the operation has been analyzed for lateral direction. Finally, the conclusion has been added based on studies presented in the paper.

2. Optimization of ICPT system

Generally, there are a few studies [36–39] that have been conducted for complete design optimization of ICPT system. The optimization should include optimized number of turns of coils, their cross section for any desired level of power.

An optimization process is proposed in this paper. The ICPT system parameters are related to user requirements in design procedure. The system parameters considered for design are coil dimensions, winding values, frequency and the user requirements are regarded as the amount of power to be transferred, voltage rating, space available for the system and cost etc. There can many combinations of ICPT system parameters to meet the user requirement, however, this design process includes iterations to limit the use of a minimum cross section of coils and find the optimal number of turns of coils.

A methodical way to design an ICPT system is shown in Fig. 1. The initial conditions are set according to user requirement i.e. power to be transferred, load voltage, load resistance and coil dimensions are set starting preliminary with few number of turns of coils and less area of cross-sections to save the cost.

The calculation of primary inductance $L_1$ and secondary inductance $L_2$ square coils can evaluated by using Neumann’s formula.

$$L = \frac{\mu_0 N^2}{4\pi} \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint \oint 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mutual inductance between primary and secondary coils of any shape.

\[ M = \frac{\mu_0}{4\pi} N_1 N_2 \int_0^r \frac{dl \cdot dl'}{r} \]  

(4)

The calculated values can be different from actual values of mutual inductance. Finite element method (FEM) is used in JMAG electromagnetic software to get the most precise value of mutual inductance. In next step, the Eqs. (2)–(4) are used to calculate the values of primary, secondary, and mutual inductance based on the defined geometry. The values of \( L_1 \), \( L_2 \), and \( M \) are used in following ICPT system equations in (5) to (15) to find system parameters.

The coupling coefficient \( k \), that defines the extent of coupling of the primary and secondary coil, is given by:

\[ k = \frac{M}{\sqrt{L_1 L_2}} \]  

(5)

The total impedance of the equivalent circuit for given parameters may be calculated as:

\[ Z_{SS} = \left( R_i + j \left( L_i \omega - \frac{1}{C_1 \omega} \right) \right) + \frac{j \omega^2 M^2}{R_i + j \left( L_2 \omega - \frac{1}{C_2 \omega} \right) + R_i} \]  

(6)

The current absorbed from the supply is given by:

\[ I_i = \frac{V_i}{Z_{SS}} \]  

(7)

The circuit is operating at a resonant frequency \( f_0 \) and the LC components cancel out their reactance and \( I_i \) is given by:

\[ I_i = \frac{V_i}{R_i + \frac{(2\pi f_0)^2 M^2}{R_i + R_L}} \]  

(8)

The input power can be calculated as:

\[ P_{IN} = \frac{V_i^2}{R_i + \frac{(2\pi f_0)^2 M^2}{R_i + R_L}} \]  

Or:

\[ P_{IN} = \frac{V_i^2 (R_i + R_L)}{R_i R_L + R_i R_L + (2\pi f_0)^2 M^2} \]  

Likewise, the output power can be obtained as below:

\[ P_{OUT} = \frac{V_i^2 (2\pi f_0)^2 M^2 R_L}{(R_i R_L + R_i R_L + (2\pi f_0)^2 M^2)^2} \]  

(9)

(10)

(11)

And the efficiency of the system can be represented by the following equation:

\[ \eta = \frac{P_{OUT}}{P_{IN}} \]  

(12)

Or:

\[ \eta = \frac{R_L}{R_i + R_L (\frac{((2\pi f_0)^2 M^2)}{R_i R_L})^2 + R_L} \]  

(13)

The maximum load resistance for optimized efficiency can be obtained by:

\[ R_L = 1 + \frac{\sqrt{\frac{(2\pi f_0)^2 M^2}{R_i R_L}}} \]  

(14)

And, thus, the maximum efficiency can be obtained as:

\[ \eta_{max} = \frac{\sqrt{\frac{(2\pi f_0)^2 M^2}{R_i R_L} + \sqrt{(R_i R_L)^2}}}{\sqrt{\frac{(2\pi f_0)^2 M^2}{R_i R_L}}} \]  

(15)

The system parameters are compared with the pre-defined requirements. The power transferred should meet the required power level and secondary voltage should not exceed the rated load voltage. The frequency should be in within permissible limit to avoid field exposure to any living thing. The geometry of coils should fit the space available at the required place. If the optimal parameters are suitable and meet the requirements, then next step is to develop the prototype or if these values do not satisfy the conditions, the iterations will be performed in Matlab program until the required conditions are met.

The optimization iteration in Matlab program provided the following values of electrical parameters and geometrical dimensions of coils given in Table 1. Based on these optimal values, the prototype will be developed for analysis and validation.

3. Analysis of optimal parameters

Based on the optimization the data of ICPT of electrical parameters has been taken into account to analyze the effect of various parameters on efficiency and power transfer capability.

3.1. Impact of air gap on coupling coefficient and mutual inductance

The coupling coefficient between the primary and secondary can be calculated from Eq. (5). If no coupling exists between the primary and secondary, then \( M = 0 \), and, thus \( k = 0 \). The general transformers with cores and no air gap have the highest coupling coefficient. The coupled coils have \( k \geq 0.5 \), they are termed as tightly coupled and those having \( k \leq 0.5 \) are loosely coupled. The value of \( M \) and thereby \( k \) depends on the physical dimensions and the number of turns of each coil, their relative position to one another and the magnetic properties of the core on which they are wound. There is also a probable decrease in the coupling coefficient due to misalignment between the transmitting coil and receiving coil in both the static and dynamic charging of EVs.

Table 1
Optimal values of electrical parameters and geometrical dimensions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of turn in primary coil</td>
<td>( N_1 )</td>
<td>7</td>
</tr>
<tr>
<td>Number of turn in secondary coil</td>
<td>( N_2 )</td>
<td>18</td>
</tr>
<tr>
<td>Cross section area of primary coil</td>
<td>( S_1 (m^2) )</td>
<td>66.6</td>
</tr>
<tr>
<td>Cross section area of secondary coil</td>
<td>( S_2 (m^2) )</td>
<td>76.6</td>
</tr>
<tr>
<td>Length of primary coil</td>
<td>( l_1 (m) )</td>
<td>0.4</td>
</tr>
<tr>
<td>Width of primary coil</td>
<td>( w_1 (m) )</td>
<td>0.4</td>
</tr>
<tr>
<td>Length of secondary coil</td>
<td>( l_2 (m) )</td>
<td>0.4</td>
</tr>
<tr>
<td>Width of secondary coil</td>
<td>( w_2 (m) )</td>
<td>0.4</td>
</tr>
<tr>
<td>Primary inductance</td>
<td>( L_1(\mu H) )</td>
<td>325</td>
</tr>
<tr>
<td>Secondary inductance</td>
<td>( L_2(\mu H) )</td>
<td>64</td>
</tr>
<tr>
<td>Mutual inductance</td>
<td>( M(\mu H) )</td>
<td>28.5</td>
</tr>
<tr>
<td>Coupling factor</td>
<td>( k )</td>
<td>0.2034</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>( V_1(V) )</td>
<td>220</td>
</tr>
<tr>
<td>Power output</td>
<td>( P_{OUT}(kW) )</td>
<td>1</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>( f(kHz) )</td>
<td>20</td>
</tr>
<tr>
<td>Primary capacitance</td>
<td>( C_1(nF) )</td>
<td>194</td>
</tr>
<tr>
<td>Secondary capacitance</td>
<td>( C_2(nF) )</td>
<td>990</td>
</tr>
</tbody>
</table>
Fig. 2, shows the variation of coupling coefficient and mutual inductance as a function of variable distance.

3.2. Impact of frequency on power transferred and efficiency of ICPT system

From the plot between frequency and efficiency shown in Fig. 3, it can be observed the optimal resonant frequency is 20 kHz which enables the possible largest power transfer. This plot has been plotted SS topology, however once a resonant frequency has been found later it easier to analyze the behavior of other compensation topologies through the implementation of respective compensation topology.

3.3. Impact of coupling coefficient on efficiency of ICPT system

Eq. (13) can be simplified to determine the reliance of the efficiency of the ICPT system on the coupling coefficient. The relationship between the coupling coefficient (k) and efficiency of power transferred can be represented by Eq. (16):

$$ \eta = \frac{R_k k^2 (2 \pi f)^2 L_1 L_2}{(R_k + R_L)R_L + R_R R_L + k^2 (2 \pi f)^2 L_1 L_2} \quad (16) $$

Fig. 4 highlights the relationship in above equation, it can be observed that the efficiency of ICPT system holds its highest value at particular resonant frequency. It is important to notice that the system designed with different coupling coefficient achieve high efficiency at same frequency. However, the bandwidth the resonance of ICPT system depends on coupling coefficient i.e. higher for larger coupling coefficients.

Although ICPT systems having coupling coefficients near to unity achieve higher efficiency but a trade-off is to be selected between efficiency and coupling coefficient depending on specific requirement of air-gap in user end application.

4. Experimental results

A series-series compensated ICPT system is constructed to transfer the power of 1 kW. Fig. 5 shows the block diagram of experimental setup. The complete schematic diagram of the experimental setup and all hardware components employed for the implementation of the project are shown in Fig. 6 and Fig. 7 respectively. The circuit is supplied through DC power supply TDK Lambda which is fed from the utility grid. The DC supply is capable of delivering up-to-the 3 kW. The DC supply feeds the DC-AC high-frequency inverter which is connected to ICPT coils. The values of electrical parameters are selected from optimized data. The resonant frequency of operation of the system has been
optimized to 20 kHz. All the experimental results are taken from oscilloscope LeCroy and power analyzer WT1800.

It is observed during the operation of the ICPT system that the voltage across capacitor and coil can be many times greater than supply voltage in series LC circuit and this is termed as "Resonant rise in voltage. The selected air cored coils can sustain the voltage across them, however, the capacitors are chosen carefully in order to get an accurate value of capacitance and to sustain the voltage stress across them. For resonant frequency operation, the capacitor chosen for the primary coil is 196 nF and for secondary coil 1038 nF. From the simulation, the
voltage across the capacitors reaches up to 2 kV.

The square geometry coil has been employed to test the performance of the ICPT system at a power level of 1 kW. The main waveforms of an experimental prototype of ICPT system for inverter output and secondary coil output are presented in Fig. 8 and Fig. 9 respectively. The input and output waveforms of ICPT system have maintained approximately unity power factor. The value of capacitance is chosen properly so that it operates at the resonance frequency and compensates the effect of leakage reactance and enables efficient power transfer.

The circuit has been tested with a various air gap between primary and secondary coil, starting from 150 mm to 300 mm. Fig. 10, shows the efficiency of square coils ICPT system at different air gaps. For 150 mm air gap, the efficiency reaches to 90.5% and for 300 mm air gap, the efficiency drops to 82%. Usually, in commercialized cars, there is an air gap of 150–250 mm between vehicle chassis and road. Thus, the air gap in the study has been considered for EV charging application. Magnetic shielding would be required to avoid the effects of magnetic field on the chassis of the car. However in this study, a tesla meter (ME 3830B) has been used to check the magnetic field intensity in the vicinity. The maximum magnetic field is recorded in the center of the air gap between coils i.e. 247 nT, thus, the magnetic field around the prototype can be considered as safe and lies within the limits prescribed by safety regulation authorities for wireless charging. Thus, in this study, the shielding has not been considered.

5. Verification of misalignment tolerance

To validate the performance of optimal coils for misalignment tolerance an ICPT prototype model has been developed. The model is shown in Fig. 11, which provides flexibility to move both primary and secondary coil with respect to each other. In shown model, there are slots to adjust the primary coil to vary the air-gap. To change the air gap, the position of the primary coil is shifted in either upward or downward direction to decrease and increase the air gap respectively. On the secondary side, nine incandescent lights of 60 W are connected as a load.

The experimental prototype model is designed for horizontal misalignment, thus, the secondary coil with incandescent lights is moved back and forth to test the misalignment tolerance. There is possible arrangement to test misalignment between coils at different steps. Fig. 12 shows the perfect alignment of the primary and secondary coil when both are centered at 70 cm marked point. At this point, the coupling coefficient is $k = 0.203$ and maximum power is being transferred.

Fig. 13 shows 25% misalignment between coils and power transfer efficiency drops to 83.5% which may be considered good for EV charging application.

However when the coils are misaligned to more than 35–40% of the
secondary coil size as shown in Fig. 14, the power transfer efficiency drops to 72%. The efficiency becomes less than 50% when misalignment becomes more than half of the coil size as shown in Fig. 15.

The results of ICPT system with optimal values are compared with previous work done in ICPT system. The parameters comprising coil dimensions, efficiency and misalignment tolerance have compared and tabulated in Table 2.

6. Conclusion

This paper has presented an optimization technique to design the ICPT system for any power level by taking application requirement into account. This technique was used to optimize the electrical parameters, and coil dimensions for 1 kW power level.

A prototype based on the optimal dimensions and electrical parameters was constructed and tested. The obtained results support the proposed technique and achieved. The experiments carried out for the ICPT system with proposed design have achieved maximum efficiency of 90.5% for 1 kW power transfer. The prototype was also tested for misalignment tolerance. The optimal coil design were observed to sustain relatively good efficiency till 40% of misalignment. The ICPT system achieved maximum efficiency of 72% where counted with 40% misalignment.

7. Future recommendations

Some recommendations for future studies can be made from the observations and results obtained from this study, which are summarized below.

7.1. In this research study, the air cored coil designs have been studied and analyzed and due to low electromagnetic field (EMF) exposure, the shielding was not considered. The proposed designs have good performance using air cored coils, however, to commercialize the
technology it is necessary to provide the shield from EMF. Thus, the proposed coil designs with embedded ferrite core should be considered for future research. Moreover, it will improve the coupling coefficient by shaping the magnetic field.

7.2. The proposed designs have enhanced the misalignment tolerance of the ICPT system designed for charging of static EV, however, the designs can be applied for charging of moving EV. So, the designs should be tested on a developed prototype of dynamic ICPT system.

To get the precise values and evaluation of ICPT system parameters, it is recommended to perform Finite Element Method (FEM) analysis of the proposed coil designs in electromagnetic simulation software. It will provide precise and accurate values and huge choice for development of innovative designs of the charging coils.

7.3. A robust control for regulation of amount of power according to State-of-Charge (SOC) of the battery is suggested.

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