THE EFFECT OF RESONANCE CIRCUIT ON INDUCTIVE EV CHARGING SYSTEMS: A SPECIFIC REVIEW

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Abstract
The resonance circuit’s design has a major influence on the inductive electric vehicle (EV) charging system’s performance and the distance between the primary and secondary inductive coils. If resonance circuitry is not included in an inductive power transfer (IPT) system, its performance suffers dramatically and its power transfer efficiency suffers significantly. Furthermore, the design of the resonance circuit has a major impact on the rating as well as the voltage and current strains on the semiconductor switches. The sequence, amplitude, and shape of the waveform are determined by the configuration of the energy storage components. The arrangement of these components is critical in defining how the inductive power transfer system behaves and operates. A few popular architectures play an important role in shaping how the system works. In this paper, the significance and effect of resonance circuits on the inductive charging of electric vehicles have been reviewed and discussed comprehensively. Furthermore, a detailed discussion was presented for the second-order resonance circuit, the higher-order resonance circuit, and the hybrid resonance circuit. Additionally, H-bridge resonant inverter topology was discussed and three main resonant architectures for the H-bridge inverter were studied inclusively. They include the inductor-capacitor-inductor (LCL) resonance architecture, switched inductor-capacitor (SLC) resonance architecture, and High-gain resonance architecture. Also, a comparison of these architectures was done and represented in tabular form. Lastly, an analysis of the effect of frequency variations in the resonant circuit architectures.

1.0 INTRODUCTION
Charging of EVs wirelessly has made waves in international research over the past few decades [1–3]. The technique is frequently utilized in several major applications which include powering of biomedical devices, mobile phones, electric vehicles, aircrafts etc. Resonance enhanced inductive power transfer systems are used to wirelessly charge electric automobiles [4–6]. This is mostly utilized for near field misalignment [7,8]. In contrast to other wireless power transfer technologies, the resonant inductive power transfer systems exhibit high power transmission capabilities [9–12]. At his laboratory, Nikola Tesla powered an incandescent lamp using electrodynamic induction in the year 1891 [13,14]. The Tesla coil, a high voltage resonant transformer was developed by Tesla and in the year 1897 it was patented. UC Berkeley launched the PATH program in the year 1970, which carefully examined the inductive power transfer technique [14].
In 1990, a prototype test track for a road was constructed; a transmission efficiency 60% was obtained. The gap between the transmitting and the receiving coil was not up to 10 cm in this experimental analysis. A similar experiment was performed at the University of Auckland in 1993, Professors John Boys and Grant Covic designed an experimental prototype capable of high-power transmission in a wide air gap [15,16]. At the Massachusetts Institute of Technology, Marin Soljacic and his group utilized tightly coupled resonators to transfer power wirelessly, in the year 2006. Most key research issues, including power transfer effectiveness and power flow control under the condition of coil mismatch, have been addressed in this field of study [17,18]. The system is made up of a high-frequency inverter on the transmitter side and a resonant converter on the receiver side and the coil both the transmitter and receiver sides are separated by an inductive airgap[19,20].

This airgap distance is approximately the same as the distance of the vehicle from the road to the chassis. An inverter is utilized for generating high frequency (HF) AC and delivered to the inductive primary coils. The generated HF voltage is transmitted to the secondary coil by induction and then rectifiers are used to convert it back to DC voltage and filtered before it is transmitted to charge the batteries of the EV [21, 22]. Essentially, the wireless charger system is built upon the synthesis of the theoretical principles of Faraday and Ampere. However, when the airgap distance is very large, the wireless charger without resonance becomes less efficient.

In this paper, section 1 gives an overview of resonant inductive charging of electric vehicles highlighting key benefits, and the typical architecture of the resonant inductive charging. In section 2, the relevance and effect of resonance circuits in EV charging systems were analyzed and several architectures were evaluated and compared including the second-order resonance architecture, the higher-order resonance circuit architecture and the hybrid resonance circuit architecture. Furthermore, in section 3 the H-bridge resonant architecture was discussed and three main resonant architectures for the H-bridge inverter were studied inclusively. They include the LCL resonance architecture, SLC resonance architecture, and High-gain resonance architecture. Also, in section 3 a comparison of these architectures was done and represented in tabular form. In section 4, the effect of varying the resonance frequency was discussed. Lastly, section 5 gives an analysis of the effect of frequency variations in the resonant circuit architectures.

1.1 Benefits of Inductive EV Charging
There are several benefits wireless charging technologies have over wired charging systems [23]. Some of these benefits include:

i. Autonomous—wireless chargers are autonomous. They can automatically charge vehicles immediately after vehicles are detected.

ii. Weatherproof protection—the coil is embedded along the surface of the road. Hence, it is not affected by atmospheric weather conditions.

iii. Anti-vandalism—the charging system cannot be easily tampered with by vandals as it is not exposed but embedded.

However, more improvement in the IPT systems is required in the following areas:

i. Detection of foreign objects—it is necessary for the system to be able to detect obstacles in between the coils that may limit power transfer efficiency.

ii. Initial implementation cost.

iii. The efficiency of the inductive power transfer technology over wired charging.

iv. The power density of the inductive power transfer mechanism.

These areas require significant improvement. Power electronic converters are essential for achieving high power density and improved power transfer efficiency. To make IPT systems feasible, numerous obstacles need to be overcome. They include electromagnetic compatibility issues and environmental conditions that may affect coils.

1.2 Typical IPT Architecture for EV Charging
Improvised designs of the IPT system have been made possible by a meaningful configuration of the energy storage components and semiconductor devices [24–26]. The compensation at the receiver side is intended to increase the power transfer efficiency while the compensation at the transmitting side lowers the VA rating [27]. Nonetheless, in the event of misalignment, the operating frequency can be changed to preserve uniformity in the power transfer level. The primary power supply’s size, scope, location, and frequency are determined by the topologies of the power converters and the path impedance. Inductor-Capacitor-Inductor (LCL), Switched Inductor-Capacitor (SLC), and Capacitor-Inductor-Inductor (CLC) topologies are mostly used in practice [28,29]. LCL is mostly preferred and efficient for various forms of load, while SLC-based resonance has poor performance for light loads [30,31]. Therefore, the topology of each converter and their architectures has a major impact on how well the wireless power transfer system performs [32,33]. Figure 1 presents
the schematic representation of an inductive EV charger system.

Figure 1: Schematic of an inductive EV charger system [30].

The AC source power goes through an uncontrolled rectifier that has a filter connected to it. Also, power factor correction is done at the input power stage. Furthermore, Figure 1 illustrates how the rectified DC voltage is transformed into a high-frequency AC voltage using a high-frequency inverter which is fed into the resonance circuit and then to the transmitting coil. At the receiver side, the receiver pickup coil, resonance circuit, and an uncontrolled bridge rectifier having a filter attached are all linked up and then connected to the load. Depending on the necessity for power flow regulation, the receiver side rectifier may be controlled or uncontrolled [34,35]. A boost converter is used at times in more contemporary applications to increase quality factors and regulate the flow of power before the load is connected.

The schematic shown in Figure 1 illustrates the significance of the resonance in the IPT system[36]. As a result, the resonance circuit is crucial in inductive power transfer systems. Also, the topologies of the resonance circuit are also vital. This research work goes into great detail about the importance of evaluating the order and architectures of energy storage components with power semiconductor devices. Additionally, various converter circuit topologies alongside their mode of operations and advantages are thoroughly discussed [37–40].

### 2.0 IMPACT OF RESONANCE CIRCUIT ON INDUCTIVE EV CHARGING SYSTEMS

The design of the resonance circuit has a significant impact on the performance of the inductive power transfer (IPT) system and the spacing between the primary and secondary inductive coils [41–43]. An IPT system's performance will suffer greatly and its power transfer efficiency will be significantly decreased if resonance circuitry is not included. Furthermore, the rating and the voltage and current stresses on the semiconductor switches are significantly influenced by the design of the resonance circuit. The configuration of the energy storage components engenders the pattern, amplitude, and shape of the waveforms [44]. The configuration of these elements is significant in determining how the wireless charger behaves and functions. A few common topologies are crucial in determining how the system functions. The total efficacy and efficiency of the inductive power transfer process are probably enhanced by these topologies.

#### 2.1 Basic Architectures of Second-Order Resonance Circuit

A circuit that contains two energy-storage components that can be characterized through second-order differential equations is referred to as a second-order resonance circuit. A second-order resonance circuit consists of three fundamental parts: an inductor, a capacitor, and a resistor. Second-order resonance circuits come in various architectural form, including parallel and series RLC circuits. One example of a second-order circuit that may be coupled in many topologies is the RLC filter. By monitoring the resonance peaks of the corner impedance, one may determine the impedance of a second-order resonance circuit. Usually, a combination of capacitance and inductance is used in second-order resonance to generate a resonant frequency. This resonance may be achieved using a variety of circuit topologies; some popular circuit topologies for second-order resonance are as follows: Series-Series, Series-Parallel, Parallel-Series, and Parallel-Parallel circuit topologies. These are the main compensation of the second-order resonance topologies. The receiver side also adheres to the same pattern [45–49]. Table 1 presents a comprehensive contrast of the relevant cases based on the necessity to choose the most efficient semiconductor switches for the converter. Moreover, a better guide to choosing the semiconductor switches for the inductive power transfer system is obtained from the power level and the impedance of the different architectures.

A comprehensive contrast of various resonance architectures of second order is presented in Table 1. The particular selection of second-order resonance circuit topology is based on the demands of the application, the intended performance attributes, and efficiency factors. Because every topology has benefits and drawbacks, engineers choose the best design according on the objectives of the inductive power transmission system.
2.2 Higher Order Resonance Circuit Topologies

Circuits that exhibit higher-order resonance have a resonant activity that surpasses second-order response. To get higher-order resonance, these circuits frequently incorporate extra energy storage components like capacitors and inductors. In some applications, higher-order resonance might offer particular benefits in terms of control, waveform shaping, and filtering. The following briefly explains some instances of circuit topologies for higher-order resonance [33,36,51,52]:

i. Third-Order Resonant Circuit: this topology incorporates an extra reactive component, which may include an extra inductor or capacitor, to generate a resonant response at a third harmonic frequency.

ii. Triple-L Resonant Converter: With this topology, a circuit with third-order resonance is created by connecting three inductors either in series or parallel. It is mostly employed in High-frequency power converters.

iii. LCLC Resonant Converter: This circuit produces a higher-order resonant response by connecting two inductors and two capacitors in series or parallel.

iv. LLLC: This architecture has a capacitor and three inductors. Extra inductors are required to achieve a Higher-order resonance.

v. Higher-Order LC Filters: Higher-order configurations for LC filters are possible, using many inductors and capacitors. Waveform shaping and harmonic suppression are two common uses for these filters.

vi. Cuk Resonant Converters: One kind of resonant converter that can display higher-order resonant behavior is the Cuk converter. It is renowned for its capacity to deliver voltage step-down or step-up conversion and has several energy storage components.

vii. Interleaved Higher-Order Resonant Converters: Interleaved converters with higher-order resonance may be created by interleaving several stages, with each having its resonant parts.

viii. Higher-Order Series Resonant Converters: To obtain higher-order resonance, series resonant converters are built with extra resonant elements or components.

In comparison to the tuning of the second-order topologies, they can be tuned more easily and are more flexible. Therefore, since the storage components present are typically greater than two, to carry out the same function additional room is needed. Higher-order resonance circuits are frequently used when certain harmonic frequencies must be suppressed or more intricate waveform shaping is required. The application's requirements, particularly the intended frequency response and performance characteristics, influence the choice of a certain higher-order resonance circuit architecture. These circuits are meticulously designed by engineers to deliver the needed functionality while reducing losses and improving efficiency [33,36], [51,52].

2.3 Hybrid Resonant Topologies

The wireless charger systems are categorized in a hierarchy of resonance when the transmitter side and receiver side circuits are taken into consideration as a whole. Nonetheless, when both the transmitter and receiver sides are analyzed independently, the order is reduced. The hybrid architecture employs both the series resonance topology and the parallel resonance topology. The compensating approach produces more efficient results. When the resonance capacitance is tuned it gives better accuracy and provides greater control flexibility. This fundamental energy storage component configuration can be coupled in the wireless charging system's transmitter and receiver sides. The system's overall efficiency would be distinct under these scenarios. The series-series combination, on the other hand, is the best primary compensation for higher power levels. If there is a sequence of parallel combinations, it can be entirely modified to provide the desired performance. By selecting the proper resonance topology, the inductive charger system may be used in a variety of applications, with LCL-based inductive charger systems having an optimal and robust performance in a wide range of applications [51,53].

Table 1: Comparison between different fundamental second-order resonance architectures [14, 50]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Series-Series</th>
<th>Series-Parallel</th>
<th>Parallel-Series</th>
<th>Parallel-Parallel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter Voltage</td>
<td>Lesser DC link voltage (greater than Series-Parallel)</td>
<td>Low DC link voltage</td>
<td>Requires higher voltage than Series-Series and Series-Parallel</td>
<td>Requires higher voltage than Series-Parallel and Series-Series</td>
</tr>
<tr>
<td>Merits</td>
<td>Output current is not influenced by the load during resonance. Also, at higher frequencies, it demonstrates high efficiency</td>
<td>Smaller pickup coil compared to SS. The parallel resonant converter at the receiver end gives a steady current</td>
<td>Easy to tune</td>
<td>Easy to tune</td>
</tr>
<tr>
<td>Demerits</td>
<td>Pickup coils are big</td>
<td>DC components are unrestrained</td>
<td>Requires current source input to mitigate</td>
<td>The power factor is low</td>
</tr>
</tbody>
</table>
3.0 DIFFERENT RESONANCE ARCHITECTURE FOR H-BRIDGE INVERTER BASED WIRELESS CHARGER SYSTEM

An essential component of electric car inductive charging is resonant converters. They are employed to wirelessly move electricity from the charging station to the car's battery. For effective power transmission, the impedance of the charging pad and the battery must match, and this is done via the resonant converter. For safe and efficient battery charging, a constant voltage between the battery terminals is also maintained with the aid of the resonant converter. It accomplishes this by controlling the current that passes through the battery and the charging pad. Furthermore, resonant converters are employed to reduce the amount of electromagnetic interference (EMI) produced throughout the charging procedure. This is critical because electromagnetic interference (EMI) can harm an automobile's electrical systems and interact with other wireless gadgets. All things considered, resonant converters are a crucial part of electric car inductive charging systems, and their significance cannot be overemphasized [38,39].

Compared to ordinary converters, the resonant converters' semiconductor switches are subjected to higher voltage stress. In a similar vein, high-frequency alternating current is also produced by AC-AC matrix converters [54,55]. More switching occurrences distort the waveform, which raises the distortion factor and lowers the system's total power factor [56]. The procedure is simpler than it was previously due to the composition of the semiconductor switches, particularly the usage of wide-bandgap semiconductors [57–59]. The circuit's resonance at the intended operating frequency is produced by the power semiconductor devices and energy storage components [60]. Compared to an IPT system without resonance, the resonance-enhanced IPT system based on an H-bridge inverter shows superior power transfer efficiency. Operating the IPT system under various loading situations is made possible by the potential of unique hybrid resonance topologies[51].

![Image](https://example.com/image.png)

**Figure 2:** H-bridge inverter based wireless charger system [30, 61]

3.1 LCL Resonance Architecture

Figure 2 depicts the generalized H-bridge inverter structure. Figure 3 displays the configuration of the energy storage components for the corresponding LCL resonance structure. The hybrid resonance topology receives the input AC voltage Vs [61 - 62]. This topology is actually an LCL topology with LCC
compensation. The primary equivalent inductance is mathematically expressed as:

\[ L_{peq} = L_p - \frac{1}{\omega^2 C_p L} - \frac{1}{\omega^2 C_r} \]  

(3)

Specifically, the layout of the energy storage components may be used to generate the second order resonance in the IPT with a different combination. Depending on how the energy storage units are arranged, resonance combinations discussed in Table 1 may be conceivable [63 – 65]. While providing a high load, the (SLC) architecture provides an optimal performance. In a similar vein, the converter's light load efficiency is low.

3.3 High-Gain Resonance LCL Architecture

High DC–DC voltage gain is specifically achieved via the high-gain LCL architecture. Consequently, the necessary input voltage level is lowered. Figure 5 displays the high-gain LCL-architecture's simplified circuit.

The computational representation of the primary compensation capacitance \( C_p \) is given as:

\[ C_p = \frac{L_{seq}}{\omega^2 L_{dp} L_{seq} M^2} \]  

(6)

The parallel capacitor at the transmitter provides greater reactive power than the traditional one due to the modification made to the standard LCL arrangement. The bidirectional flow of current is facilitated by the combination of semiconductor switches that are coupled back-to-back. The
equivalent secondary capacitance can be expressed as follows:
\[
C_{seq} = \frac{1}{\omega^2 C_{eq}} \tag{8}
\]

\(C_{eq}\) represents the effective equivalent of \(C_g\) and \(C_p\) combined. The reflected capacitance in each of these architectures is expressed as:

\[
C_r(M, R_{eq}) = \frac{R_{eq}(w^2C_{seq}L_{seq}^{-1})^2 + (wL_{seq})^2}{(w^2M^2)C_{eq}R_{eq}(w^2C_{eq}L_{seq}^{-1})^2 + (wL_{seq})^2} \tag{9}
\]

The reflected capacitance is a product of the mutual inductance, as shown by Equation (9). The mismatched distance between the coils determines the mutual inductance. Moreover, reflected capacitance determines the resonance operating frequency [23]. The reflected resistance \(R_r(M, R_{eq})\) is therefore expressed as follows:

\[
R_r(M, R_{eq}) = \frac{R_{eq}(w^2C_{seq}L_{seq}^{-1})^2 + (wL_{seq})^2}{(w^2M^2)C_{eq}R_{eq}(w^2C_{eq}L_{seq}^{-1})^2 + (wL_{seq})^2} \tag{10}
\]

Under misalignment, the high-gain LCL resonance architecture has a larger voltage gain than the traditional LCL and SLC resonance architectures. Even at a weakly linked range, the voltage gain is larger than with the other popular design. Ultimately, this renders the converter advantageous for a wireless charger system that exhibits significant misalignment. The part that depends on \(R_{eq}\) disappears when the term in denominator \(w^2C_{seq}L_{seq}\) approaches 1 during the resonance period. This ultimately indicates that the system's resonance frequency will not be affected by variations in load during the resonance. The relationship between mutual inductance and primary current determines the open circuit voltage. As a result, in a system with loose coupling, the secondary current is likewise decreased. The primary current's amplitude and operation frequency are significantly influenced by the secondary resonance topology. The secondary circuit components' configuration is used to determine the reflected capacitance [23].

### Table 2: Comparison of different H-bridge resonance circuit architectures [66]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LCL</th>
<th>LCL High Gain</th>
<th>SLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>1 kW</td>
<td>1 kW</td>
<td>1 kW</td>
</tr>
<tr>
<td>Frequency</td>
<td>85 kHz</td>
<td>85 kHz</td>
<td>85 kHz</td>
</tr>
<tr>
<td>Efficiency</td>
<td>76-90%</td>
<td>74-87%</td>
<td>76-90%</td>
</tr>
<tr>
<td>Voltage Gain</td>
<td>0.25-0.5</td>
<td>0.6-2.1</td>
<td>0.3-0.7</td>
</tr>
<tr>
<td>Semiconductor Devices</td>
<td>8</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Energy Storage Elements</td>
<td>9</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Voltage stress across the resonant inverter (V_{ac}/2)</td>
<td>(V_{dc}/2)</td>
<td>(V_{ac}/2)</td>
<td></td>
</tr>
<tr>
<td>Coupling coefficient</td>
<td>0.1-0.25</td>
<td>0.1-0.25</td>
<td>0.1-0.25</td>
</tr>
<tr>
<td>Preferred load</td>
<td>Heavy load</td>
<td>Heavy load</td>
<td>Light load</td>
</tr>
<tr>
<td>Complexity of Circuit</td>
<td>Simple</td>
<td>Simple</td>
<td>Complex in control</td>
</tr>
</tbody>
</table>

### 3.4 Comparison of the discussed H-bridge resonance architectures

Each architecture offers different advantages depending on the kind of load attached to it. Based on several relevant criteria, the current dominating topologies are compared; the results are displayed in Table 2 [66].

### 4.0 EFFECT OF RESONANCE FREQUENCY VARIATION

To understand the efficient working range, one needs to understand the operating and resonance frequency. The notation for the resonance frequency is given mathematically as [48,49]:

\[
\omega_0 = \frac{1}{\sqrt{L_{eq}C_{eq}}} \tag{11}
\]

Where, the equivalent effective inductance is represented as \(L_{eq}\) while the effective equivalent capacitance is captured as \(C_{eq}\) respectively and they are both evaluated in accordance to the architecture of the circuit. Variation in frequency as a result of variations in coil misalignment has been studied for the LCL-based inductive power transfer circuit [67].

Figure 6: Operating frequency versus coil misalignment [67] (a) Horizontal misalignment of coils, (b) Vertical misalignment of coils
MOSFET’s material also has a significant impact on the system’s overall efficiency. This lowers the system’s likelihood of switching losses even further. SiC-based MOSFETs would be recommended for greater voltage stress and high operating frequency applications. GaN-based MOSFETs are recommended if switching speed is a key consideration. Consequently, this raises the degree of power transmission from one circuit to another [51].

5.0 CONCLUSION AND RECOMMENDATIONS

In conclusion, inductive power transfer systems must have a resonant circuit and a certain architecture to achieve the best possible power transfer efficiency and distance. The configuration of energy storage components and the application of common topologies also have a major impact on how well the system performs. Resonant converters are a crucial component of electric vehicle inductive charging. They are used to transmit power wirelessly from the charging station to the car's battery. The impedance of the charging pad and the battery must match for successful power transfer, which is accomplished via the resonant converter. A constant voltage between the battery terminals is also maintained with the help of the resonant converter for safe and efficient battery charging. It achieves this by regulating the current flowing through the battery and charging pad. In addition, resonant converters are used to limit the amount of electromagnetic interference (EMI) generated during the charging process. This is important because electromagnetic interference (EMI) can damage an automobile's electrical systems and interfere with other wireless devices.

Resonant power inverter and other EV chargers are being developed with the primary goals of achieving high power density, cheap cost, small size, and high efficiency. Effective and reliable control schemes must be created for the resonant inverter-based EV chargers (LLC or CLLC) in order to achieve these goals. Efficient bidirectional resonant converters must be created in order to improve system dependability and offer ancillary services such as reactive power support, harmonic correction, voltage difference, and frequency deviation reduction.

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