Nigerian Journal of Technology (NIJOTECH)
Vol. 43, No. 2, June, 2024, pp.317 - 327
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
https://doi.org/10.4314/njt.v43i2.15

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

AUTHORS:
O. Akpeghagha[1,*], C. M. Nwosu[2], and E. C. Ejiogu[3]

AFFILIATIONS:
[1,2,3]Africa Centre of Excellence for Sustainable Power and Energy Development, University of Nigeria, Nsukka.

***CORRESPONDING AUTHOR:**
Email: akpeghagha.oghenevwaire.pg02690@unn.edu.ng

ARTICLE HISTORY:
Received: 02 February, 2024.
Revised: 22 April, 2024.
Accepted: 08 May, 2024.
Published: 12 June, 2024.

KEYWORDS:
Resonance, Inductive, Electric Vehicle, Charging, Semiconductor, Resonant Inverter, Inductive Power Transfer.

ARTICLE INCLUDES:
Peer review

DATA AVAILABILITY:
On request from author(s)

EDITORS:
Ozoemena Anthony Ani

FUNDING:
None

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].

HOW TO CITE:
Akpeghagha, O., Nwosu, C. M., and Ejiogu, E. C. "The Effect of Resonance Circuit on Inductive EV Charging Systems: A Specific Review", *Nigerian Journal of Technology*, 2024; 43(2), pp. 317 – 327; https://doi.org/10.4314/njt.v43i2.15

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 environme-ntal 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-Capacitor (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.

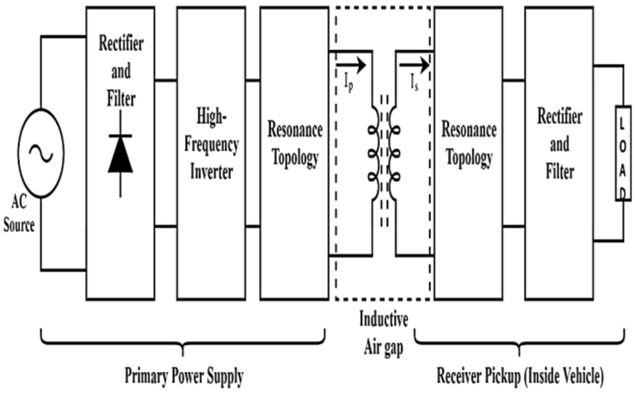

Figure 1: Schematic of an inductive EV charger system [30].

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 atimes 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]

	Resonance Architectures			
Parameters	**Series-Series**	**Series-Parallel**	**Parallel-Series**	**Parallel-Parallel**
Inverter Voltage	Lesser DC link voltage (greater than Series-Parallel)	Low DC link voltage	Requires higher voltage than Series-Series and Series-Parallel	Requires higher voltage than Series-Parallel and Series-Series
Merits	Output current is not influenced by the load during resonance. Also, at higher frequencies, it demonstrates high efficiency	Smaller pickup coil compared to SS. The parallel resonant converter at the receiver end gives a steady current	Easy to tune	Easy to tune
Demerits	• Pickup coils are big	DC components are unrestrained	• Requires current source input to mitigate	• The power factor is low

	• The loads are not influenced by the voltage transfer ratio at partial loading scenario.		momentary fluctuations in voltage • Input resistance is high and hence requires a high input voltage	• Needs a high current source • Input resistance is high and hence requires a high input voltage
Impedance (z)	Lesser	Lesser	Higher	Higher
Power transfer efficiency	Higher	Higher	Lesser	Lesser
Efficiency for larger distance between coils	Lesser	Lesser	High	High
Output independent by load	Voltage and current	Voltage and current	Voltage	Current
Applications	Static/Dynamic EV Charging	Biomedical applications, Low power transport	High-power EV applications	High-power EV applications

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].

The high-frequency H-bridge resonant inverter receives a rectified DC voltage (V_{DC}) from a connected rectifier supply. The output voltage (V_s) of the inverter has a V_{DC} RMS value. Moreover, a resonance is generated by the resonant branch according to the configuration of the energy storage components. The following computational analysis is true generally[51].

$$v_s = V_s \sin 2\pi f_0 t \quad (1)$$

The V_s is written in V_{DC} as:

$$V_s = \frac{2\sqrt{2}\,V_{DC}}{\pi} \sin \frac{\omega_0\, t_{PS}}{2} \quad (2)$$

Where, t_{PS} refers to the phase shift time delay in the gate pulse. Similarly, f_0 is the resonance frequency of operation of the inverter in Hz. ω_0 is the resonance frequency of operation in rad/sec. The following is a list of three notable resonance architectures discussed in this review paper:

i. LCL resonance architecture.
ii. SLC resonance architecture.
iii. High-gain resonance architecture.

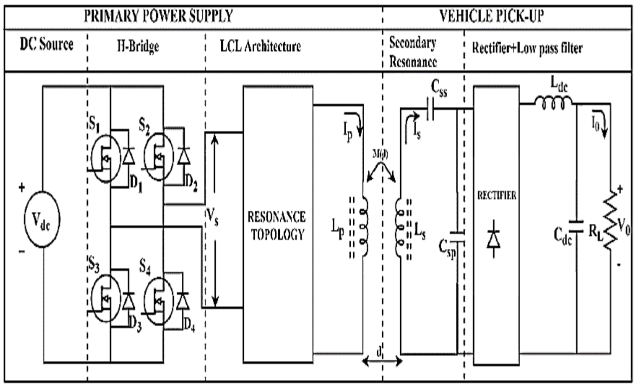

Figure 2: H-bridge inverter based wireless charger system [30, 61]

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:

$$L_{peq} = L_P - \frac{1}{\omega^2 C_{PL}} - \frac{1}{\omega^2 C_r} \quad (3)$$

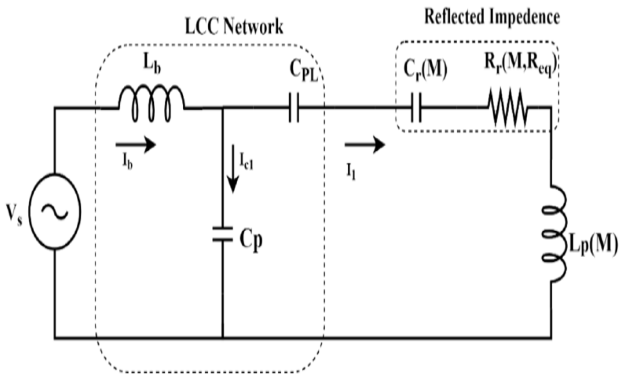

Figure 3: An equivalent circuit illustration of LCL architecture [30]

The series capacitor at the transmitter side is espressed as:

$$C_{ps} = \frac{L_{seq}}{\omega_0^2 [L_{\Delta p} L_{seq} - M^2]} \quad (4)$$

$$L_{peq} = \frac{1}{\omega^2 C_{pp}} \quad (5)$$

Where, C_{pL} refers to the primary series tuning capacitor. The mutual inductance between the primary coil and the secondary coil is represented as M and the reflected capacitance is shown as C_r. A corresponding primary inductance is created by modifying the circuit's series capacitance and primary inductor. The H-bridge inverter's current is constrained by the bridge inductor L_b. The primary equivalent inductor L_{peq} and the capacitor C_p are in resonance. The LCL-based wireless charger system can function throughout a broad load range by fine-tuning the primary compensation capacitances. The misalignment influences the reflected capacitance. There are very small variations in equivalent inductance as a result of the large misalignment changes. This gradually lessens the amount of frequency shift required for the operation to sustain resonance under misalignment.

3.2 SLC Resonance Architecture

Another resonance topology that is popularly utilized with the H-bridge inverter is the SLC Resonance architecture. Figure 4 depicts the configuration of the energy storage components for the corresponding SLC resonance architecture.

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

$$C_p = \frac{L_{seq}}{\omega_0^2 [L_{\Delta p} L_{seq} - M^2]} \quad (6)$$

where the major equivalent inductance-related change in inductance value is expressed as:

$$L_{\Delta p} = L_p - L_{peq} \quad (7)$$

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.

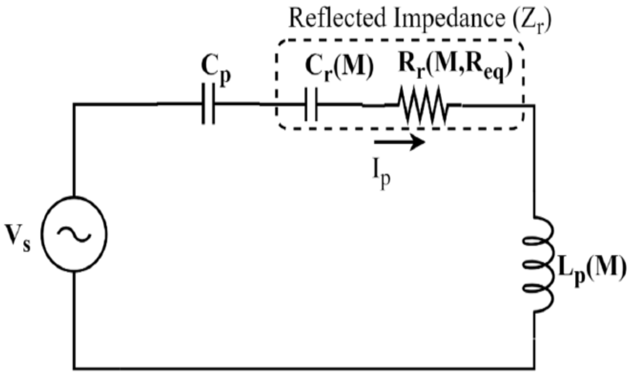

Figure 4: Simplified equivalent circuit of SLC architecture [30]

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.

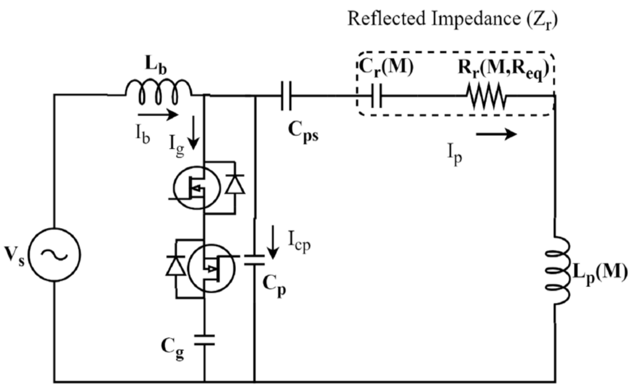

Figure 5: Simplified circuit of high-gain LCL architecture [20]

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:

$$C_{seq} = \frac{1}{\omega^2 C_{eq}} \quad (8)$$

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

$$C_r(M, R_{eq}) = \frac{R_{eq}^2(w^2C_{sp}L_{seq}-1)^2+(wL_{seq})^2}{(w^4M^2)[C_{sp}R_{eq}^2(w^2C_{sp}L_{seq}-1)^2+L_{seq}]} \quad (9)$$

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:

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

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 $w^2C_{sp}L_{seq}$ 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]

Parameters	LCL	LCL High Gain	SLC
Power	1 kW	1 kW	1 kW
Frequency	85 kHz	85 kHz	85 kHz
Efficiency	76-90%	74-87%	76-90%
Voltage Gain	0.25-0.5	0.6-2.1	0.3-0.7
Semiconductor Devices	8	10	8
Energy Storage Elements	9	10	9
Voltage stress across the resonant inverter	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$
Coupling coefficient	0.1-0.25	0.1-0.25	0.1-0.25
Preferred load	Heavy load	Heavy load	Light load
Complexity of Circuit	Simple	Simple	Complex in control
Relevance for dynamic wireless charging	Good	Good	Not preferred

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]:

$$\omega_r \frac{1}{\sqrt{L_{eq}C_{eq}}} \quad (11)$$

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].

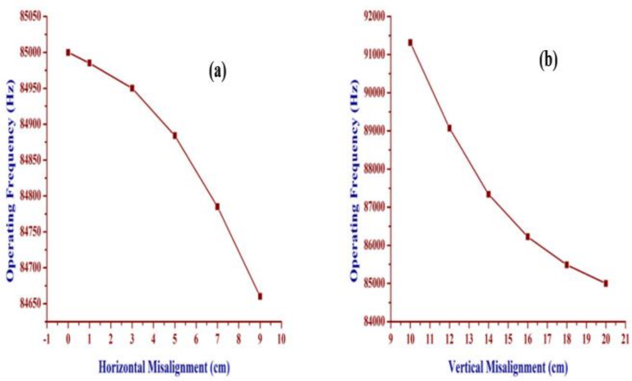

Figure 6: Operating frequency versus coil misalignment [67] (a) Horizontal misalignment of coils, (b) Vertical misalignment of coils

Figure 6 (a and b) illustrates the obtained result. Under the matching frequencies to the associated misalignment, the circuit will maintain its resonance condition. Expanding the operating frequency enhances the power transmission capacity over longer distances.

It is crucial to choose switches based on how frequently they operate to ensure that the circuit functions as intended. Normally, the higher frequency makes it impossible to achieve this using power IGBT. On the other hand, power MOSFETs with shorter turn-on times are particularly preferred. The power

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 inverters 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 reactive power support, harmonic correction, voltage difference, and frequency deviation reduction.

REFERENCES

[1] R. Bosshard and J. W. Kolar, "Inductive Power Transfer for Electric Vehicle Charging: Technical Challenges and Tradeoffs," *IEEE Power Electron. Mag.*, vol. 3, pp. 22–30, 2016.

[2] I. Mayordomo, T. Drager, P. Spies, J. Bernhard, and A. Pflaum, "An Overview of Technical Challenges and Advances of inductive Wireless Power transmission," *Proc. IEEE*, vol. 101, pp. 1302–1311, 2013.

[3] J. Dai and D. C. Ludois, "A Survey ofWireless Power Transfer and a Critical Comparison of Inductive and Capacitive Coupling for Small Gap Applications," *IEEE Trans. Power Electron.*, vol. 30, pp. 6017–6029, 2015.

[4] C.-S. Wang, G. A. Covic, and O. . Stielau, "Investigating an LCL Load Resonant Inverter for Inductive Power Transfer Applications.," *IEEE Trans. Power Electron.*, vol. 19, pp. 995–1002, 2004.

[5] O. Knecht and J. W. Kolar, "Performance Evaluation of Series-Compensated IPT Systems for Transcutaneous Energy Transfer.," *IEEE Trans. Power Electron.*, vol. 34, pp. 438–451, 2018.

[6] B.-H. Choi, E. S. Lee, J. Huh, and C. T. Rim, "Lumped Impedance Transformers for Compact and Robust Coupled Magnetic Resonance Systems," *IEEE Trans. Power Electron*, vol. 30, no. 1, 2015.

[7] A. A. S. Mohamed, A. Meintz, P. Schrafel, and A. Calabro, "Testing and Assessment of EMFs and Touch Currents From 25-KW IPT System for Medium-Duty EVs.," *IEEE Trans. Veh. Technol.*, vol. 68, pp. 7477–7487, 2019.

[8] V. Prasanth and P. Bauer, "Distributed IPT Systems for Dynamic Powering: Misalignment Analysis.," *IEEE Trans. Ind. Electron*, vol. 61, pp. 6013–6021, 2014.

[9] H. H. Wu, A. Gilchrist, K. D. Sealy, and D. Bronson, "A High Efficiency 5 KW Inductive Charger for EVs Using Dual Side Control.," *IEEE Trans. Ind. Inf*, vol. 8, pp. 585–595, 2012.

[10] L. Huang, A. P. Hu, A. Swain, and X. Dai, "Comparison of Two High Frequency Converters for Capacitive Power Transfer.," in *2014 IEEE Energy Conversion Congress and Exposition (ECCE), Pittsburgh*, 2014, pp. 5437–5443.

[11] A. Banerji, T. Datta, G. Bandyopadhyay, S. K. Biswas, and A. Banerji, "Wireless Transfer of Power: Status and Challenges.," in *2016 International Conference on Intelligent Control Power and Instrumentation (ICICPI), Kolkata, India.*, 2016, pp. 251–257.

[12] H. Funato, H. Kobayashi, and T. Kitabayashi, "Analysis of Transfer Power of Capacitive Power Transfer System.," in *2013 IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS), Kitakyushu, Japan*, 2013, pp. 1015–1020.

[13] A. Marincic, "Nikola Tesla and the Wireless Transmission of energy," *IEEE Trans. Power Appar. Syst.*, vol. 10, pp. 4064–4068, 1982.

[14] V. Shevchenko, O. Husev, R. Strzelecki, B. Pakhaliuk, N. Poliakov, and N. Strzelecka, "ompensation Topologies in IPT Systems: Standards, Requirements, Classification, Analysis, Comparison and Application," *IEEE Access*, vol. 7, pp. 120559–120580, 2019.

[15] D. Patil, M. K. McDonough, J. M. Miller, B. Fahimi, and P. T. Balsara, "Wireless Power Transfer for Vehicular Applications: Overview and challenges," *IEEE Trans. Transp. Electrif.*, vol. 4, pp. 3–37, 2018.

[16] J. T. Boys and G. A. Covic, "The Inductive Power Transfer Story at the University of Auckland," *IEEE Circuits Syst. Mag.*, vol. 15, pp. 6–27, 2015.

[17] J. M. González-González, A. Triviño-Cabrera, and J. A. Aguado, "Design and Validation of a Control Algorithm for a SAE J2954-Compliant Wireless Charger to Guarantee the Operational Electrical Constraints," *Energies*, vol. 11, p. 604, 2018.

[18] A. Cai, A. Pereira, R. Tanzania, Y. K. Tan, and L. Siek, "A High Frequency, High Efficiency GaN HFET Based Inductive Power Transfer System," in *2015 IEEE Applied Power Electronics Conference and Exposition (APEC), Charlotte*, 2015, pp. 3094–3100.

[19] M. Lu and K. D. . Ngo, "Systematic Design of Coils in series–series Inductive Power Transfer for Power Transferability and Efficiency," *IEEE Trans. Power Electron*, vol. 33, pp. 3333–3345, 2018.

[20] S. Varikkottil and J. F. Daya, "High-gain LCL Architecture Based IPT System for Wireless Charging of EV," *IET Power Electron*, vol. 12, pp. 195–203, 2019.

[21] A. Trigui, S. Hached, F. Mounaim, A. C. Ammari, and M. Sawan, "Inductive Power Transfer System with Self-Calibrated Primary Resonant Frequency," *IEEE Trans. Power Electron.*, vol. 30, pp. 6078–6087, 2015.

[22] T. Mishima and E. Morita, "High-Frequency Bridgeless Rectifier Based ZVS Multiresonant Converter for Inductive Power Transfer Featuring High-Voltage GaN-HFET," *IEEE Trans. Ind. Electron*, vol. 64, pp. 9155–9164, 2017.

[23] V. Cirimele, O. Smiai, P. Guglielmi, F. Bellotti, R. Berta, and A. De Gloria, "Maximizing Power Transfer for Dynamic Wireless Charging Electric Vehicles," in *Electrical Engineering and Applied Computing; Springer Science and Business Media LLC: Berlin/Heidelberg*, 2018, pp. 59–65.

[24] G. Kkelis, D. C. Yates, and P. D. Mitcheson, "Class-E Half-Wave Zero dv/Dt Rectifiers for Inductive Power Transfer.," *IEEE Trans. Power Electron*, vol. 32, pp. 8322–8337, 2017.

[25] M. Liu, M. Fu, and C. Ma, "Parameter Design for a 6.78-MHzWireless Power Transfer System Based on Analytical Derivation of Class E Current-Driven Rectifier," *IEEE Trans. Power Electron.*, vol. 31, pp. 4280–4291, 2016.

[26] S. Varikkottil and J. L. FebinDaya, "Compact Pulse Position control-based Inverter for High Efficiency Inductive Power Transfer to Electric Vehicle," *IET Power Electron.*, vol. 13, pp. 86–85, 2020.

[27] C.-S. Wang, O. H. Stielau, and G. . Covic, "Design considerations for a contactless electric vehicle battery charger," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1308–1314, 2015.

[28] H. Feng, T. Cai, S. Duan, J. Zhao, X. Zhang, and C. Chen, "An LCC-Compensated Resonant Converter Optimized for Robust Reaction to Large Coupling Variation in Dynamic Wireless Power Transfer," *IEEE Trans. Ind. Electron.*, vol. 63, pp. 6591–6601, 2016.

[29] S. Samanta and A. K. Rathore, "A new current-fed CLC transmitter and LC receiver topology for inductive wireless power transfer application: analysis, design, and experimental results," *IEEE Trans. Transp. Electrif.*, vol. 1, no. 4, pp. 357–368, 2015.

[30] B. Esteban, M. SidAhmed, and N. C. Kar, "A Comparative Study of Power Supply Architectures in Wireless EV Charging systems.," *IEEE Trans. Power Electron.*, vol. 30, pp. 6408–6422, 2015.

[31] Z. Shuai, D. Liu, J. Shen, C. Tu, Y. Cheng, and A. Luo, "Series and Parallel Resonance Problem of Wideband Frequency Harmonic and Its Elimination Strategy," *IEEE Trans. Power Electron.*, vol. 29, pp. 1941–1952, 2013.

[32] J. Deng, W. Li, S. Li, and C. Mi, "Magnetic Integration of LCC Compensated Resonant Converter for Inductive Power Transfer Applications.," in *2014 IEEE Energy Conversion Congress and Exposition (ECCE), Pittsburgh, PA, USA, 14–18 September 2014; Institute of Electrical and Electronics Engineers (IEEE): Piscataway*, 2014, pp. 660–

667.

[33] Z. Pantic, S. Bai, and S. Lukic, "ZCS LCCLCC-Compensated Resonant Inverter for Inductive-Power-Transfer Application," *IEEE Trans. Ind. Electron*, vol. 58, pp. 3500–3510, 2010.

[34] M. Fan, L. Hi, Z. Yin, L. Jiang, and F. Zhang, "Improved Pulse Density Modulation for Semi-Bridgeless Active Rectifier in in-Ductive Power Transfer system," *IEEE Trans. Power Electron*, vol. 34, pp. 5893–5902, 2019.

[35] K. Colak, E. Asa, and D. Czarkowski, "A Novel Phase Control of Single Switch Active Rectifier for Inductive Power Transfer Applications," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA.*, 2016.

[36] E. M., "Higher-Order Topological Electric Circuits and Topological Corner Resonance on the Breathing Kagome and Py- Rochlore lattices," *Phys. Rev. B.*, vol. 98, pp. 201–402, 2018.

[37] S. Varikkottil and J. . Febin Daya, "Estimation of optimal operating frequency for wireless EV charging system under misalignment," *Electronics*, vol. 8, no. 3, p. 342, 2019.

[38] I. 60364-7, "Requirements for Special Installations or Locations," *IEC: Geneva, Switzerland*. 2017.

[39] J. M. Stankiewicz and A. Choroszucho, "Comparison of the Efficiency and Load Power in Periodic Wireless Power Transfer Systems with Circular and Square Planar Coils," *Energies*, vol. 14, pp. 49–75, 2021.

[40] W. Zhang, S. C. Wong, C. Tse, and Q. Chen, "Analysis and Comparison of Secondary Series- and Parallel-Compensated Inductive Power Transfer Systems Operating for Optimal Efficiency and Load-Independent Voltage-Transfer Ratio," *IEEE Trans. Power Electron.*, vol. 29, pp. 2979–2990, 2014.

[41] T. Nagashima, X. Wei, T. Suetsugu, M. K. Kazimierczuk, and H. Sekiya, "Waveform Equations, Output Power, and Power Con-Version Efficiency for Class-E Inverter Out-Side Nominal operation," *IEEE Trans. Ind. Electron.*, vol. 61, pp. 1799–1810, 2014.

[42] T. Nagashima, X. Wei, E. Bou, E. Alarcon, M. K. Kazimierczuk, and H. Sekiya, "Steady-State Analysis of Isolated Class-eˆ2 Converter Outside Nominal operation," *IEEE Trans. Ind. Electron*, vol. 64, pp. 3227–3238, 2017.

[43] S. Aldhaher, P. Luk, K. E. K. Drissi, and J. Whidborne, "High-Input-Voltage High-Frequency Class E Rectifiers for Resonant Inductive Links," *IEEE Trans. Power Electron.*, vol. 30, pp. 1328–1335, 2014.

[44] P. C. K. Luk and S. Aldhaher, "Analysis and Design of a Class D Rectifier for a Class E Driven Wireless Power Transfer System," *2014 IEEE Energy Convers. Congr. Expo. (ECCE), Pittsburgh, PA.*, pp. 851–857, 2014.

[45] M. Goldman, P. Grandinetti, A. Llor, Z. Olejniczak, J. R. Sachleben, and J. . Zwanziger, "Theoretical Aspects of higher-order Truncations in solid-state Nuclear Magnetic Resonance," *J. Chem. Phys.*, vol. 97, pp. 8947–8960, 1992.

[46] V. Sooraj, "A Study of Magnetic Coupling and Selection of Operating Frequency for Static and Dynamic EV Charging System," in *2016 International Conference on Circuit, Power and Computing Technologies (ICCPCT), Nagercoil, India*, 2016, pp. 1–4.

[47] K. Aditya, V. K. Sood, and S. S. Williamson, "Magnetic Characterization of Unsymmetrical Coil Pairs Using Archimedean Spirals for Wider Misalignment Tolerance in IPT Systems," *IEEE Trans. Transp. Electrif.*, vol. 3, pp. 454–463, 2017.

[48] N. Jamal, S. Saat, and A. Z. Shukor, "A Study on Performances of Different Compensation Topologies for Loosely Coupled Inductive Power Transfer System," in *2013 IEEE International Conference on Control System, Computing and Engineering, Penang,Malaysia*, 2013, pp. 173–178.

[49] B. X. Nguyen, W. Peng, and D. M. Vilathgamuwa, "Multilevel Converter Topologies Based High Power Inductive Power Transfer Systems," in *2016 IEEE International Conference on Sustainable Energy Technologies (ICSET), Hanoi, Vietnam*, 2016, pp. 264–269.

[50] Y. J. Hwang and J. Y. Jang, "Design and Analysis of a Novel Magnetic Coupler of an In-Wheel Wireless Power Transfer System for Electric Vehicles," *Energies*, vol. 13, no. 332, pp. 1–21, 2020.

[51] S. Varikkottil *et al.*, "Role of Power Converters in Inductive Power Transfer System for Public Transport — A Comprehensive Review," *Symmetry (Basel).*, vol. 14, no. 508, pp. 1–24, 2022.

[52] H. Feng, T. Cai, S. Duan, and E. Al., "An LCC compensated resonance converter optimized for robust reaction to large coupling variation in dynamic wireless power transfer," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6591–6601, 2016.

[53] S. Varikkottil and F. D. J. L, “Compact pulse position control-based inverter for high efficiency inductive power transfer to electric vehicle,” *IET Power Electron.*, pp. 86–95, 2019.
[54] M. Kazimierczuk and J. Jozwik, “Resonant DC/DC Converter with Class-E Inverter and Class-E Rectifier,” *IEEE Trans. Ind. Electron.*, vol. 36, pp. 468–478, 1989.
[55] N. X. Bac, D. M. Vilathgamuwa, and U. K. Madawala, “A SiC-Based Matrix Converter Topology for Inductive Power Transfer system,” *IEEE Trans. Power Electron.*, vol. 29, pp. 4029–4038, 2014.
[56] M. Moghaddami and A. I. Sarwat, “Single-Phase Soft-Switched AC–AC Matrix Converter with Power Controller for Bidirectional Inductive Power Transfer Systems,” *IEEE Trans. Ind. Appl.*, vol. 54, pp. 3760–3770, 2018.
[57] M. Moghaddami, A. Anzalchi, and A. I. Sarwat, “Single-Stage Three-Phase AC–AC Matrix Converter for Inductive Power Transfer Systems,” *IEEE Trans. Ind. Electron.*, vol. 63, pp. 6613–6622, 2016.
[58] H. L. Li, A. P. Hu, and G. A. Covic, “A Direct AC–AC Converter for Inductive Power-Transfer systems,” *IEEE Trans. Power Electron.*, vol. 27, pp. 661–668, 2012.
[59] R. Bosshard and J. W. Kolar, “All-SiC 9.5 kW/Dm3On-Board Power Electronics for 50 kW/85 KHz Automotive IPT System,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 5, pp. 419–431, 2017.
[60] D. C. Yates, S. Aldhaher, and P. D. Mitcheson, “A 100-W 94% Efficient 6-MHz SiC Class E Inverter with a Sub 2-W GaN Resonant Gate Drive for IPT,” in *2016 IEEE Wireless Power Transfer Conference (WPTC), Aveiro, Portugal*, 2016, pp. 1–3.
[61] M. Furitsch *et al.*, “Comparison of Degradation Mechanisms of Blue-Violet Laser Diodes Grown on SiC and GaN Substrates,” *Phys. Status Solidi (a)*, vol. 203, pp. 1797–1801, 2006.
[62] M. Moghaddami, A. Cavada, and A. I. Sarwat, “Soft-Switching Self-Tuning H-Bridge Converter for Inductive Power Transfer Systems,” in *2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, USA*, 2017.
[63] J.-H. Lu *et al.*, “Research on Seamless Transfer from CC to CV Modes for IPT EV Charging System Based on Double-Sided LCC Compensation Network,” in *2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, USA*, 2016, pp. 1–6.
[64] Y. Yao, X. Liu, Y. Wang, and D. Xu, “Modified Parameter Tuning Method for LCL/P Compensation Topology Featured with load-independent and LCT-unconstrained Output Current,” *IET Power Electron.*, vol. 11, pp. 1483–1491, 2018.
[65] X. del Toro García, J. Vázquez, and P. Roncero-Sánchez, “Design, Implementation Issues and Performance of an Inductive Power Transfer System for Electric Vehicle Chargers with series–series compensation,” *IET Power Electron.*, vol. 8, pp. 1920–1930, 2015.
[66] S. A. Sabki and N. M. L. Tan, “Performance Improvement of Electric Vehicle Inductive-Power Transfer System Using Series-Series Capacitor Compensation,” in *2015 IEEE Conference on Energy Conversion (CENCON), Johor Bahru, Malaysia*, 2015, pp. 66–71.
[67] S. Varikkottil and J. L. Febin Daya, “Estimation of Optimal Operating Frequency forWireless EV Charging System under Misalignment,” *Electronics*, vol. 8, p. 342, 2019.