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TOPICAL REVIEW

A Comprehensive Review on Efficiency Enhancement of Wireless Charging System for the Electric Vehicles Applications

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ABSTRACT The increasing Electric Vehicle (EV) market is driven by the desire for more efficient and reliable approaches to recharge EV batteries. Among various charging methodologies for EVs, Wireless Power Transfer (WPT) has gained more attention from EV users due to its features such as safety, low maintenance, comfort, automated operation, and reliability. The innovative WPT method replaces the conductive charging system while maintaining a similar power rating and efficiency. Numerous strategies have been devised to enhance the efficiency and reliability of the WPT model. The primary challenge in WPT is reduction in power transfer efficiency (PTE) as the gap between the coils is increased. Also, the improvement in the PTE depends on various design parameters of the WPT circuit. Therefore, this review article thoroughly investigates recent significant research literatures that explains WPT technology and tailored towards enhancement of PTE. The investigation is carried on various coil configurations, converter topologies and different critical factors to improve PTE such as impedance matching, compensation techniques. Moreover, the research gaps in WPT technology and future scope suitable for static, quasi-dynamic, and dynamic charging methods are presented. This research can play a crucial role in assisting developers in selecting an optimal design to enhance the WPT system.

INDEX TERMS Wireless power transfer, impedance matching, compensation techniques, efficiency improvement, electric vehicle, electric vehicle charging.

I. INTRODUCTION

Electric vehicles (EVs) are becoming more popular across the variety of fields, as they offer numerous benefits over conventional gasoline-based vehicles. However, EVs have limitations such as limited range, lack of charging infrastructure. Automotive industries are making significant strides in addressing the limitations of EVs [1], [2], [3], [4]. In addition, the expansion of the charging infrastructure, efficient charging methodologies with optimal cost are essential. EV charging can be more convenient, effective and efficient with wireless power transfer (WPT) based charging technology [5]. Additionally, power can be easily scaled to match with the any type of EV charging.

Wireless charging technology has the potential to make electric vehicles more convenient, safe, and efficient. As the

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technology continues to develop and the cost decreases, wireless charging is likely to become more widespread in the future. However, this technology has main hurdle, which is poor efficiency due to weak coupling between transmitter (Tx) and Receiver (Rx). In the recent years many researches where undergone to improve the power transfer efficiency (PTE). This motivates the author to present a review article on improvement techniques for PTE in wireless charging of EV. The maturity of WPT is significantly increasing after the society of automotive engineers (SAE) developed the standards for wireless charging SAEJ2954 [6]. Figure 1 shows the block diagram of Inductive resonant power transfer (IRPT) based charging system for an EV [7].

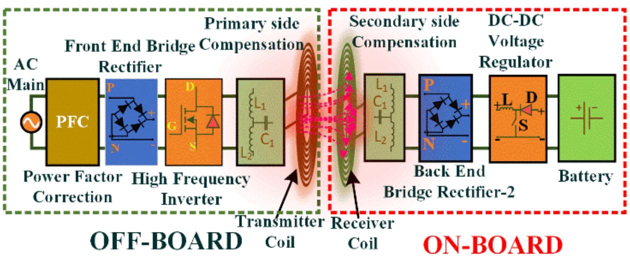


FIGURE 1. Inductive resonant power transfer based wireless charging system.

The transmitter side of the system is comprised of three major blocks: Power factor correction block, front end AC/DC bridge rectifier, and DC/AC high frequency inverter. The power factor correction block maintains voltage and current always in line. Mainly, it is used to improve the power quality of the grid supply, which is achieved by using combinational circuits with an external capacitor. The AC/DC rectifier converts the incoming alternating current (AC) to direct current (DC), which is then fed to the DC/AC inverter which changes the DC back to high-frequency AC power. On the receiver side, the wireless charging system comprises an AC/DC bridge rectifier, a DC/DC regulator and a battery load for charging applications. The AC/DC rectifier converts the high-frequency AC signal that is received from the transmit loop coil into DC. The DC/DC converter tunes the voltage of the DC to match the requirements of the charging load, which is typically the battery is replenished with the energy received from the wireless charging system. To enable wireless charging, an AC/DC rectifier needs to be activated with a power source. However, the global commercial AC operates at a frequency that is insufficient to support wireless charging, which is either 50 or 60 Hz. To overcome this issue, the wireless charger changes the AC to DC and then elevates the frequency of the transformed power to high frequency AC. The high frequency AC then runs through the transmit loop coil, which creates a magnetic field around it. The receive loop coil, separated from the transmit coil by an air gap, converts the induced AC to DC and reshapes it to meet the voltage requirements of the load. The energy receiver then replenishes the battery of an EV, completing the wireless charging process [8], [9], [10], [11], [12].

A. SURVEY COMPARISON

The existing review articles on WPT charging for EVs focus on charging methods of EVs, Challenges on WPT, coil geometry for WPT, and compensation topologies. Limited literature focused on PTE & misalignment tolerance improvement and multi-coil WPT system. Table 1 portrays the summary of survey articles conducted in the last five years on wireless charging of EV. Patil et al. [13] reviews about charging pads, compensation topologies, standards, impedance matching, power electronics converters and its controls. Suggests the challenges in the implementation of dynamic WPT. Concluded that the high cost, human exposure to EMF and absence of adequate communication are major limiting factors while implementing dynamic WPT. Ahmad et al. [14] surveyed the different wireless charging technologies for EV. Outlined the standards, compensation, roadblocks in coil pad design, frequency selection, misalignment tolerance and economic analysis. Author concluded with finding out the major research gaps, such as 1. Design of efficient coil with optimal size 2. Impact of high frequency electro-magnetic fields on communication system 3. Coil alignment 4. Foreign object detection 5. Misalignment tolerance. Mahesh et al. [15] gives the comparative review on inductive pads, standards, compensation configuration and rails. Concluded with few highlights of research gap to be addressed in future research in the way of improvement in safety and health, fast charging, interoperability, cyber security, scheduling algorithm, and economical aspects. Mohamed et al. [16] gives comparative survey on coil parameters, compensation topologies for both static and dynamic WPT. It manipulates the energy of WPT system using mathematical models, verified the same with experimental results. Rahulkumar et al. [17] analysed the charging pad design in terms to the improvement of its performance for dynamic WPT system, also highlights the parameters which affects the PTE. Shanmugam et al. [18] review various charging couplers, power converter topologies and compensation network for dynamic wireless charging system. Also author educated the designing of dynamic wireless charging system. Nguyen et al. [19] proposed the survey map for designing the wireless high-power transfer. And analysed the single and double resonance block based LC-resonant circuits. Finally with this review map suggested the different control techniques to achieve maximum efficiency. In Sagar et al. [20] reviewed compensation techniques, methods to improve misalignment tolerance, and analyzed the performance of various WPT systems which are in practice.

In this survey author beliefs that the PTE and misalignment tolerance can be enhanced by impedance matching, compensation techniques and multi-transmitter based wireless charging. Hence author gives more focus on surveying of impedance matching, compensation and multi-transmitter based wireless charging techniques for EV. Which provides

TABLE 1. Survey Comparison on wireless EV charging (✓) is indicated for topic covered (✗) is indicated for topic not covered.

Topics	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	This Article
Factors which affects transfer efficiency	×	✓	✓	×	×	×	×	×	✓
Present Standing in WPT system	×	×	×	×	×	×	×	×	✓
Types of Wireless Charging	×	✓	✓	✓	×	×	×	✓	✓
Possibilities of misalignment	×	✓	×	×	✓	×	×	✓	✓
PTE and misalignment tolerance enhancement techniques	×	×	×	×	×	×	×	×	✓
Impedance matching	✓	×	×	×	×	×	×	×	✓
Compensation techniques	✓	✓	✓	✓	×	✓	✓	✓	✓
Different methods of multi-coil WPT system	×	×	×	×	×	×	×	×	✓
Coil geometry	✓	✓	✓	×	✓	✓	×	✓	✓
Challenges for WPT charging system	✓	✓	✓	×	✓	✓	✓	✓	✓
Future scope and Research direction	×	×	✓	×	✓	✓	×	×	✓

TABLE 2. WPT system in laboratory level.

Name	Distance	Power	Frequency	Efficiency	Reference
KAIST	15cm	15kW	20kHz	80%	[21]
	20cm	20kW	20kHz	71%	[22]
ORNL	25.4cm	20kW			[23]
KRRI	5cm	818kW	60kHz	82.7%	[24]
NYU	21cm	25kW	85kHz	91%	[25], [26]
Conductix Wampfler	4cm	120kW	20kHz	90%	[27]
Fraunhofer	13.5cm	22kW	100kHz	97%	[28]
WiTricity Electric Vehicle	18cm	3.3kW	85kHz	90%	[29]
INTIS	15cm	30kW	35kHz	90%	[11]
ETH-Zurich	20cm	50kW	85kHz	95.8%	[30]
	52mm	5kW	1MHz	96.5%	[31]
PATH	7.5cm	60kW	20kHz	60%	[32]
State Key Laboratory of Power System and Generation	10cm	1.5 kW	85kHz	97%	[33]
University of Auckland	16cm	50kW	85kHz	90%	[34]
Fuzhou University	10cm	1.6kW	85kHz	92.5%	[35]
Zhejiang University	20cm	2.63kW	85kHz	91.06%	[36]
Myongji University	16cm	22kW	85kHz	95.7%	[37]
the Moroccan research institute for Solar Energy and New Energies	15-25cm	3.7kW	85kHz	90.02%	[38]
Delft University of Technology	10cm	7.2kW	86.5kHz	97.1%	[39]

detailed information on multi-transmitter based WPT for EV, future trends, and research directions in WPT for PTE enhancement, makes this article unique and informative.

B. STATE OF WPT SYSTEM FOR EV CHARGING

The remarkable achievement in-terms of developed laboratory level projects, current standings in publications and commercially developed products were surveyed and illustrated in the following table 2-4 respectively.

It is clear from above references highlighted in the table 2, efficient power transfer is possible with additional techniques like compensation topologies, operating frequency and optimal air-gap distance. However, all WPT systems are prone to misalignment which causes reduction in PTE.

As per the standard SAEJ2954 the minimum air-gap distance between transmitter and receiver is 16 cm, the references shown in table 3, investigates the performance with different couplers and variable air-gap distance. As a result of numerous researches on WPT system for EV, the table 4 gives the commercially available charging facility for the electrical vehicle. By using various topologies the PTE of the WPT system achieves around 90 %, however it may get decreases abruptly when misalignment occurs between the couplers. Therefore, the investigations are required for the betterment of the misalignment tolerance, which is addressed in this article.

C. STRUCTURE AND CONTRIBUTION

In Figure 2 the organizational structure of the proposed review article is visualized. The entire article comprises of seven section. Section I starts with introduction about the need, basic operation of WPT system. Section II gives the factors influences in PTE and improvement techniques of the WPT system. Followed by the research

TABLE 3. WPT system current standings in research publications.

Coupler	Distance	Power	Frequency	Efficiency	Reference
C-C	10cm	1kW	85kHz	95.57	[40]
DD-DD	20cm	1kW	60kHz	83%	[41]
C-C	15cm	1.6kW	150kHz	81%	[42]
DD-DD	10-25cm	2kW	20kHz	80%	[43]
C-C	20cm	2kW	20kHz	85%	[44]
S-S	15cm	3.3kW	1MHz	95%	[45]
R-C	15cm	4kW	85kHz	93%	[46]
DD-DD	15cm	5kW	20kHz	80%	[21]
C-C	16cm	5kW	20kHz	90%	[47]
R-C	13.5	22kW	100kHz	97%	[28]
R-R	20cm	50kW	85kHz	95.8% (DC-DC)	[31]
DD-DD	12.7cm	100kW	22kHz	98%	[48]
DD-DD	12.5cm	100kW	25kHz	97.7%	[49]
B-B	20cm	7.7kW	79kHz	96% (DC-DC)	[50]
C-C	13cm	1.5kW	85kHz	95.2% (DC-DC)	[51]
C-C	13cm	45W	85kHz	88%	[52]
DD-DD	16cm	50kW	85kHz	95.2% (DC-DC)	[53]
R-R	20cm	6.6kW	85kHz	94.3%	[54]
C-C	15cm	200W	55kHz	95%	[55]
R-S	21cm	11kW	85kHz	95.7%	[56]
Overlap winding in both Tx & Rx	20cm	7.7kW	86kHz	94.9%	[57]
DD-DD	16cm	6.6kW	85kHz	95.1%	[58]
B-B	10cm	500W	85kHz	>80%	[59]
S-S	10mm	400W	85kHz	87.96	[60]

TABLE 4. Commercially available inductive resonant based wireless EV charging system.

Name/Place	Power	Supply Voltage	Frequency	Air gap	Reference
WiTricity	3.6kW	240V AC	85kHz	10-25 cm	[61]
Qualcomm	3.6kW	240V AC	85kHz	16-22cm	[62]
Wave	50kW	270V AC	23.4kHz	16.5-19cm	[63]
USA	10kW	240V AC	20kHz	20 cm	[64]
USA	25kW	240V AC	20kHz	24 cm	[65]
Germany	20kW	240V AC	85kHz	16-25cm	[66]
Gotland	100kW	240V AC	85kHz	24cm	[67]

investigations on impedance matching, compensation, and multi-transmitter based WPT system were discussed in Section III, IV, and V respectively. Section VI discusses the future scope and research direction. And finally ends with conclusion in section VII. This article delve in to the development of a WPT system that is specifically for EV charging.

This article reviews the key challenges faced in attaining higher efficiency and various ways of enhancing the efficiency of WPT system. While many researchers have reviewed various WPT aspects, a thorough discussion on enhancing PTE in WPT for EV has not been presented in any study.

The highlights of this paper are as follows.

- Discussed about the various factor which affects the power transfer efficiency, and various techniques that are employed for the improvement of the power transfer efficiency in particular impedance matching techniques, Compensation topologies and multi-transmitter based WPT system.
- Discussed the various ways for matching the source impedances and load impedance for achieving the better power transfer capability. While charging the EV using WPT, maintaining of equivalent impedance value in primary coil as well as secondary coil is difficult due the variation in the clearance between the coils during parking of the vehicle over the charging pad.
- Various Compensation technique, basic topologies and hybrid topologies were discussed. Which has numerous benefits, including improved efficiency, increased stability, reduced EMI, and improved safety.
- Discussed various multi-transmitter based WPT system in the view of misalignment tolerance improvement.

The main focus is on identifying the techniques for the improvement of PTE of WPT based EV charging systems. Specifically shed light on the most effective ways to transfer

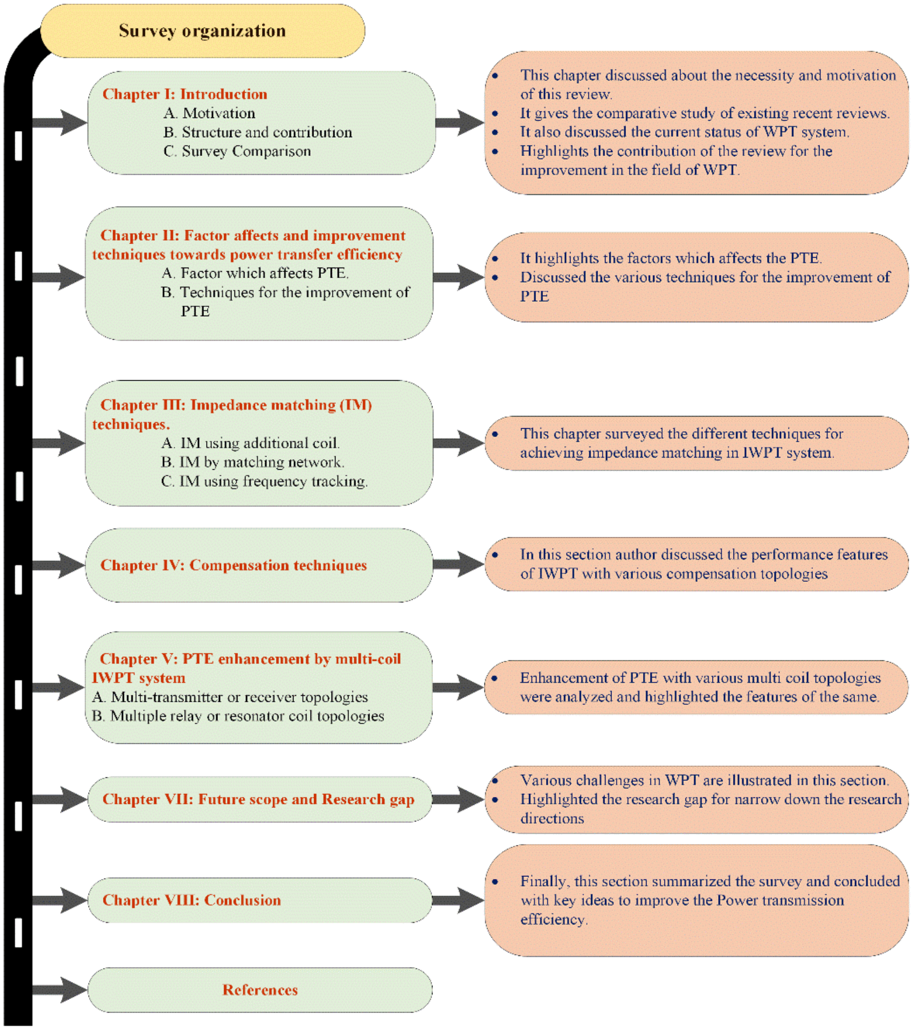


FIGURE 2. Organizational structure of the article.

power wirelessly to EV, also providing insight into the various technical challenges that must be overcome in order to achieve this goal. Overall, this review provides the additional value to researchers and developers who are working to improve the power transfer efficiency and functionality of the wireless EV charging by suggesting the survey analysis on various techniques to the improvement of PTE.

II. FACTOR AFFECTS AND IMPROVEMENT TECHNIQUES TOWARDS POWER TRANSFER EFFICIENCY

Among various charging methods, WPT charging methodology adds several features to the EV charging system. WPT methodology is the more than ten decade old technology, which undergoes continuous development till now. Based on the methodology to achieve wireless transmission and medium which may classified. In general WPT system is a core less transformer, in wireless EV charging air is acting as a core, due to its poor permeability it is necessary to utilize high operating frequency, resonance condition, and compensation.

A. FACTORS WHICH AFFECT POWER TRANSFER EFFICIENCY

Power transfer efficiency (PTE) in WPT systems is influenced by a number of different factors. Some of the key factors that can affect PTE are portrayed in the Figure 3. Which includes coupling factor, quality factor, Resonance, distance between coils, coil alignment, coil geometry, system load matching, coil material, operating power level, harmonics, interference factors and load variability.

The coupling factor (K), is used to determine the efficiency of energy transfer between two coupled coils in a magnetic system. It is an important parameter in WPT systems, the value of 'K' varies from 0 to 1. It represents the level of magnetic coupling between the transmitter and receiver coils. Stronger coupling is denoted by higher values of 'K' which can lead to better power transfer efficiency. A higher 'K' value means that there is reduced energy leakage and improved energy transfer between the coils. Quality factor (Q) is a measure of the energy losses in a resonant WPT

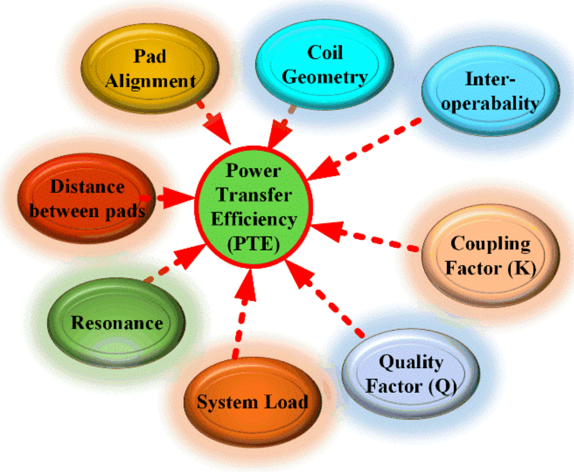


FIGURE 3. Major factors influencing for PTE in WPT systems.

system. A higher Q-factor means lower energy losses and higher power transfer efficiency. Systems with high Q-factor are capable of maintaining resonance and delivering more power to the receiver.

In WPT system, the system load refers to the electrical characteristics of the load connected to the receiver. Matching the system load with the impedance of the receiver coil is essential for optimizing PTE. A well-matched load minimizes reflection losses and maximizes power transfer. Resonant WPT systems are highly efficient because they allow for maximum energy transfer between coils at the specific frequency. Maintaining resonance is crucial for achieving high power transfer efficiency. As the transmitter and receiver pads move away with each other in a WPT system, the power transfer efficiency decreases. This happens because the magnetic field strength also decreases with distance. To overcome this, techniques like beam-forming and increasing the coil size can be used to mitigate power losses over longer distances. For efficient power transfer in a WPT system, it is crucial to have proper alignment between the transmitter and receiver pads. Misalignment can lead to reduced coupling, increased energy loss, and decreased efficiency. To maintain optimal pad alignment, technologies like dynamic alignment and tracking can be used. The efficiency of WPT systems is influence by the physical shape and size of the coil designs, coupling can be improved and energy losses can be reduced. In many cases, larger surface areas and specific geometries are employed in the design of coils to enhance power transfer efficiency. The concept of inter-operability revolves around the idea that WPT systems should be able to work with different devices and standards. This is achieved through standardization and compatibility between different WPT systems, which ensures widespread adoption and ease of use. Having a common WPT standard that can be used to charge or power multiple devices is crucial for convenience and efficiency [68], [69], [70].

B. TECHNIQUES AFFECT THE POWER TRANSFER EFFICIENCY

By taking the different factors into account, it is possible to optimize the design of a WPT system in order to achieve the highest possible level of power transfer efficiency. The enhancement of PTE in WPT systems involves carefully addressing these factors through system design, engineering, and control strategies to ensure efficient and reliable wireless power transfer. Impedance matching system is one of the crucial concept in WPT system which enhances the Coupling factor, Quality factor mean while it mitigates the setbacks caused by variation in system load, and deviation of the resonance [71], [72], [73].

Compensation technique is another crucial concept to enhancing the efficiency of WPT systems [74]. These techniques are employed to overcome the various challenges associated with wireless energy transmission. Which improves power transfer transmission distance without making any major change in the WPT system. It can be employed for any kind coil geometry, therefore which improves interoperability and misalignment tolerance.

Misalignment is a significant challenge in wireless power transfer (WPT) systems, which occurs when the transmitter and receiver coils deviate from their ideal alignment. This deviation can cause a significant reduction in PTE in WPT system. As portrayed in Figure 5. There are three main types of misalignment- radial, axial and angular.

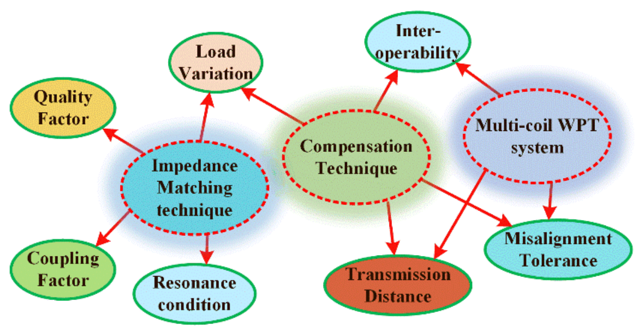


FIGURE 4. Techniques which improves the factors associated with PTE of WPT system.

In a WPT system, misalignment can occur between the transmitter and receiver coils in three ways: radial, axial, and angular. Radial misalignment happens when the coils deviate along the axis of the coils, axial misalignment occurs when the deviation is perpendicular to the axis, and angular misalignment occurs when the deviation is in the plane perpendicular to the axis. The degree of power loss due to misalignment depends on various factors such as the type of misalignment, the distance between the coils, and the frequency of operation of the power transfer. Radial misalignment has the least impact on efficiency, followed by axial misalignment, and then angular misalignment. Such misalignment tolerance can be improved by several techniques. These include using larger coils which have a larger effective area and are less sensitive to misalignment,

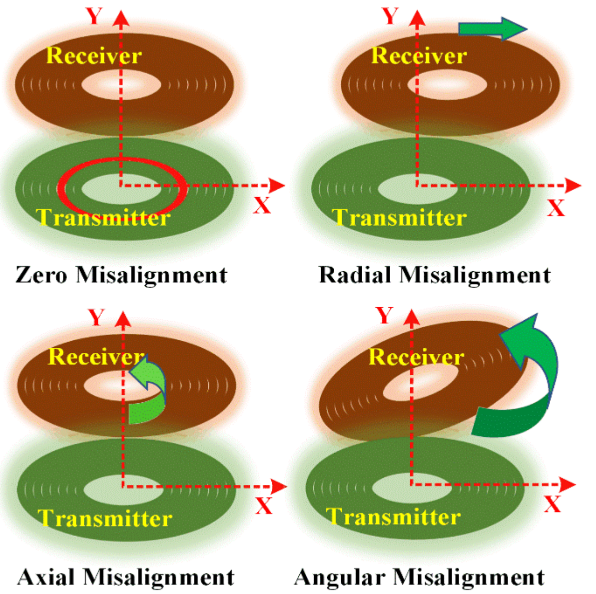


FIGURE 5. Types of Misalignment in WPT system.

using multiple coils to create a virtual coil with a large effective area, using adaptive control systems that can adjust power control systems that can adjust power transfer parameters in real time to compensate for misalignment, and using meta-materials that have tailored properties to improve WPT system performances. The choice of the technique depends on the specific application and required level of misalignment tolerance. For EV applications multi-coil technique is most suitable technique [75], [76].

Therefore, to improve the PTE of the WPT system, Impedance matching (IM), Compensation technique, and Multi-coil-based WPT system were most preferred approaches. These techniques improves majority of dependent factors of efficient power transfer capabilities, as illustrated in the Figure 4, associated with improving PTE. Multiple aspects of WPT such as applications, classifications, and market opportunities, structure of WPT, charging techniques, and factors affecting PTE of WPT have been discussed. Additionally through this survey author beliefs that the PTE and misalignment tolerance can be enhanced by multi-transmitter based wireless charging.

III. IMPEDANCE MATCHING

Impedance matching is a technique that is widely used in power transfer and communication systems to improve the transfer efficiency. As per SAE J2954 standards for light duty wireless charging the allowable variation in alignment between transmitter and receiver is ±75 mm, in x-axis and ±100 mm in y-axis to make the comfort environment for the customers in WPT system based charging stations as illustrated in table 5. Therefore, it is mandatory to design the WPT based EV charging system with prescribed misalignment tolerance without compromising the power transfer efficiency. Due to which the variation of the load impedance is takes place, and further suppress the power transfer efficiency in EV wireless charging [78], [79]. In coupled circuits maximum power is transferred when load impedance (Z_L) and the source impedance (Z_S) are equal [71]. In wireless charging of EV the process of making the source impedance and load impedance equal ($Z_S = Z_L$) to each other to maximize the power transfer capability of the system, is termed as impedance matching.

TABLE 5. Flexibility of misalignment tolerance [77].

Description	Type	Value
Lateral Misalignment in mm	*ΔX*	*±75*
	ΔY	*±100*
Angular Misalignment in degree	Roll	*±2%*
	Pitch	*±2%*
	Yaw	*±10%*
Efficiency in %	Aligned Condition	*>85 %*
	Misaligned Condition	*>80%*

Principle of Impedance Matching (IM): When an electrical power is transmitted from a grid source to an EV battery, impedance mismatch can occur, which results in a part of the power being reflected back towards the source. This reflected power can cause interference with the original power and which minimize the efficiency of the WPT based charging system. Therefore, there is a need to ensure that the impedance of the source and the load are matching, a matching network is inserted in between them. By inserting a matching network, either passive or active, the power reflection ratio to the power source of the system is reduced, which helps to maximize the power transfer between the source and EV battery. This makes the WPT system highly efficient and effective. The goal of the matching network is to ensure that the impedance of the network matches that of the source and the load. Figure 6 demonstrates the wireless charging of EV battery, the power transferred (P_o) to the EV battery, which can be represented by equation 1, Io is the output current charging the battery, while the impedance of the power source is defined as Z_S and that of the battery load is defined as Z_L. According to maximum power transfer thermo the impedances Z_L matches Z_S, and vice versa, it can lead to an improvement in efficiency. In other words, the matching network ensures that the impedance of the source and the load are equal, which results in the maximum power transfer efficiency between them.

$$P_o = I_o^2 Z_L = \left(\frac{V^2 Z_L}{(Z_S + Z_L)^2} \right) \tag{1}$$

Maximum power that can be delivered by the source when, the change in power with respect to load impedance is zero, $\frac{dP_o}{dZ_L} = 0$,

$$\frac{dP_o}{dZ_L} = \frac{V^2(Z_S + Z_L)^2 - 2Z_L(Z_S + Z_L)V^2}{(Z_S + Z_L)^4} \tag{2}$$

If $Z_L = Z_S$, from the equation (2) the change in power becomes zero, and suggests the condition for maximum power transfer. In EV wireless charging achieving this condition is difficult due to the variation of the load impedance. By using additional impedance matching network the power transfer efficiency can be achieved as illustrated in the figure 6. Based on the components used for the impedance matching which is classified into two types i) Active impedance matching ii) Passive impedance matching. Both matching techniques were employed to optimize the power transfer efficiency for the WPT system.

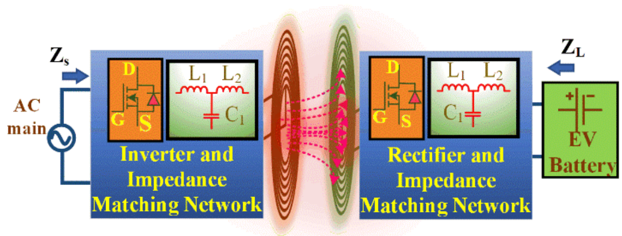


FIGURE 6. Structure of impedance matching.

In [80] proposed an adaptive impedance matching for single frequency. The required matching impedance is estimated by considering voltage input, average reactive & active power. The estimated impedance achieved practically by additional network. This proposed technique is implemented and validated with 50W prototype. In [81] instead of using expansive tunable network an active impedance comparison network is introduced which matches source and load impedance. In [82] also by adapting double side phase shift control technique is used for rectifier and matches the impedance mismatch between source and EV battery. Which is validated with 500W prototype and achieved 90.2 % efficiency. In [83] repeater coils where used to match the change in impedance due to variation in the position of the receiver coils. It demonstrated the matching of impedance accomplished through variety of combinations with variation in the coil distances. In [84] a reconfigurable resonant coil (RRC) is used to match the impedance variation occurs due to receiver coil. Also which controls both coupling factor (K) and quality factor (Q) by connecting an additional number of sub-coils and optimizes the PTE. The RRC can either be used as a single- sided matching component on the transmit side or can be placed on both transmit and receive sides to widen the IM range.

A. ACTIVE IMPEDANCE MATCHING

In active impedance matching the source and load impedances were matched by using active components such as switches, controllers to adjust the frequency, amplifiers, and reconfigurable transmitter or receiver coils etc. This matching circuits constantly monitors the operating conditions and adjusts the impedance for acquiring the maximum power transfer. Active impedance matching technique suggests high flexibility specifically were the load impedance of the WPT system varies predominantly, in the case of dynamic wireless charging.

1) ACTIVE CONTROLLED TUNING FOR INDUCTIVE CHARGING OF ELECTRIC VEHICLES

In this article an active impedance control is proposed which can able to delivers constant power to EV battery even with changes in the load impedance due to misalignment. In general for active tuning switched controlled capacitors were employed, by changing the switching frequency the required impedance were tuned. In this article tuning of impedance mismatch is achieved by controlling the phase angle (θ) between primary (V_{Pi}) and secondary (V_{Si}) input voltage by using active phase angle controlled rectifier. The phasor diagram of LCL compensated WPT system is shown in the figure 7 [85], [86].

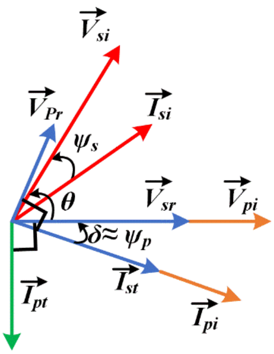


FIGURE 7. Phasor diagram of the WPT system.

The optimum value of the phase angle (θ) is obtained by "search algorithm", it works based on the search for the optimum value within the prescribed impedance limits set by secondary coil's impedance. It were executed with MATLAB simulation and validated with 7 kW prototype setup and achieved 92.7 % of DC-DC transfer efficiency with coupling coefficient (k) variation between 0.1 and 0.2.

2) IMPEDANCE MAPPED COMPENSATION NETWORK WITH DUAL PHASE SHIFT CONTROL

In this article the change of load impedance due to misalignment is compensated by impedance mapped T-compensation network connected to the secondary side of the WPT system as shown in figure. It visualized the impedance trajectory of secondary side with variation in impedance angle (θ) and confirmed the similar performance of the tunable network used in the conventional impedance matching methods. In addition with the proposed compensation network a control strategy is proposed for the secondary side full bridge active rectifier (FBAR) to achieve ZVS operation of the all switched used in this WPT system as shown in the figure 8.

Fig. 8 shows the WPT system with impedance mapping compensation network (IMTCN) connected in the secondary side and primary side is compensated with LCC compensation network. This network is built with the combination

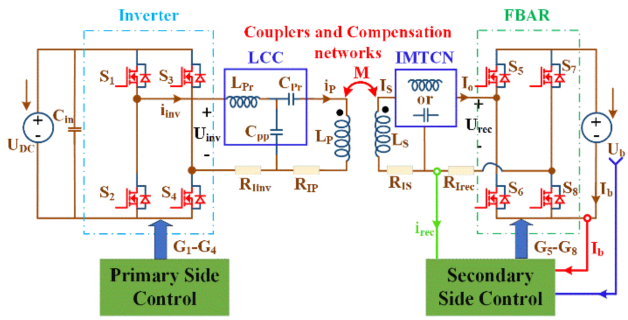


FIGURE 8. WPT system with impedance mapping compenstion network.

of passive components such as inductor and capacitor, the values of the elements are based on the WPT system parameters.

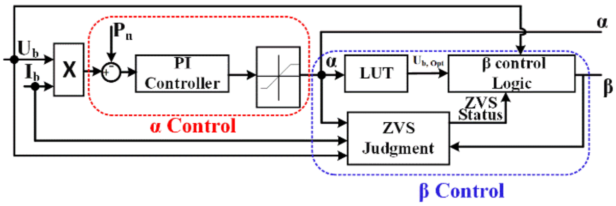


FIGURE 9. Block diagram of the pulse generation for FBAR.

The figure 9 shows the control strategy for FBAR, which finds the minimum current zone to perform the ZVS operation. Here α control is for monitoring and regulating power, β control is for monitoring and performing the ZVS operation. This system is validated with 2.2 kW prototype WPT system by performing the operation in both open loop and closed loop to analyze the importance of the proposed control strategy. Achieved the power transfer efficiency of 94.3% at 0.2 coupling factor and 92.3 % at 0.12 coupling factor [87].

3) IMPEDANCE MISMATCHE BY RESONANT FREQUENCY CONTROL

Due to the mismatch between source and load impedance the resonant condition is disturbed in both primary and secondary resonant tank. In this article proposed a control algorithm that monitors and regulates the resonant frequency by generating pulses based on the variation in impedance behaviour of the WPT system. Meanwhile the proposed control algorithm reduces the conduction losses by accomplishing zero current switching (ZCS).

As shown in the figure 10 WPT system compensated with S-S topology, the voltage across the series capacitor in the primary side is sensed and controls the frequency. If the voltage is less than zero the period is increased by one step, if it is less than zero the period is decreased by one step and for zero voltage no change is performed. The same approach is continuously followed and controls the resonant frequency and achieves the ZCS. The proposed control algorithm is confirmed with 1 kw prototype model and achieved efficiency of 90% with air gap distance of 10 cm the operating frequency is 82.42 kHz, with air gap distance of 5 cm the efficiency is reached up 98.20 % operating at 75.30 kHz [88].

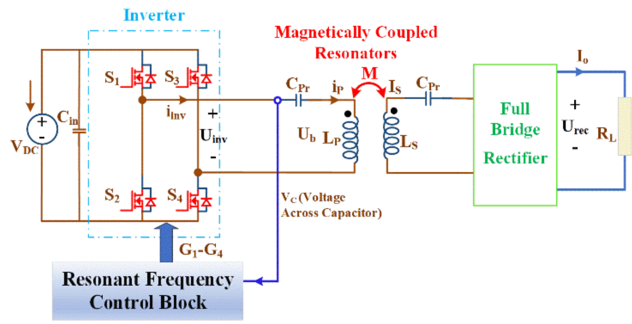


FIGURE 10. WPT system with closed loop frequency control.

4) IMPEDANCE MATCHING USING SELF-ADAPTIVE RESONANCE METHODOLOGY

In this paper a tuning circuit is used to correct the impedance mismatch caused due pad misalignment, air gap between transmitter and receiver and control techniques. The parameter of the tuning circuit is selected based on the required power transfer, operating resonance condition and mismatch values of the impedance. Proposed tuning circuit generates the voltage proportional to the lost value due to impedance mismatch, which circulates new current and regulates the resonant condition as proven by the current superposition principle.

Fig. 11 shows the self-tuning compensation circuit, which comprises of the capacitors C_2, C_3, & C_{i2} with two additional switches S_3, S_4, auxiliary inductor L_3. V_{i2} is the auxiliary voltage generated by the self-tuning circuit, i_{Z3} is the corresponding compensating current both are based on the coupler's mismatch. Which are accomplished by three stages, firstly C_{i2} absorbs the energy through switch S_3 then secondly it stores the energy absorbed until the S_4 is in ON state and finally it liberates to the transmitter circuit through S_3. The proposed system is validated with scaled down prototype model with 250W power transfer and achieved 86.4 % of DC-DC power transfer efficiency at coupling coefficient of 0.24 which is lesser than typical WPT system but author concludes that even though the efficiency value is acceptable it needs improvement. But the change in impedance is matched by adjusting the coupling coefficient between, 0.192 to 0.302 for all cases it maintains the efficiency of value around 85% [89].

B. PASSIVE IMPEDANCE MATCHING

The resonance condition of the WPT system is crucial to achieve maximum power transfer efficiency. By using additional coil approach the condition of the resonance in the circuit can be maintained effectively. The change in impedance due to misalignment or any other external facts can be compensated by adding additional coils.

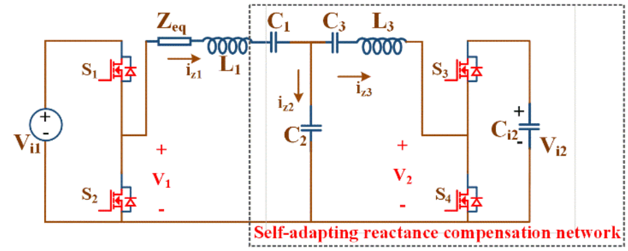


FIGURE 11. Transmitter with self-tuning compensation circuit.

1) MAXIMIZATION OF THE EFFICIENCY USING SWITCHED CONTROLLED CAPACITORS

This article proposed a control strategy to achieve maximum efficiency with constant power delivery for the LCC-LCC compensated WPT system. It replaced a main capacitor of the primary side LCC compensation with switched capacitor (C_1) as shown in the figure 12. The value of the capacitance (C_1) is controlled by adjusting the ON time and OFF time of the parallel connected back to back switches S_a and S_b, control pulses generated by the proposed control strategy.

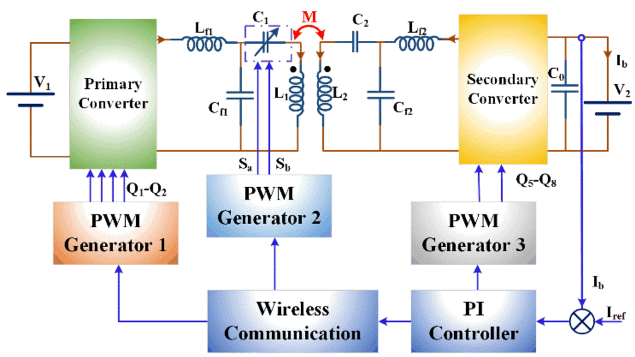


FIGURE 12. Control strategy to maximize the power transfer efficiency.

Here the battery voltage (V_2) and required battery charging current (I_b) were sensed and calculates the desired power output and load resistance of the WPT system by using simple divider and multiplier. Based on these parameters PI controller generates two control signals β_p and β_s for generating control pulses required for primary and secondary converters with ZVS operation. By considering these control signals the generated PWM pulse operates the switched capacitors as shown in the figure 12. This proposed system is validated with 6.6 kW WPT system model tested with D-D coil coupler and achieved 95.1 % efficiency with 0.3 coupling factor [58].

2) IMPEDANCE MATCHING USING DRIVER COIL

In this article author gives contribution to the improvement of WPT for charging the autonomous mobile robot. The mismatching of impedance occurs due to the movement of robot, and power reflection causes reduction of power transfer. This impedance mismatch is compensated by using driver coil, which is place over the transmitter coil as shown in the figure. Additional coil makes changes in the total impedance of the transmitter coil in accordance with receiver coil's impedance. The coupling coefficient between driver coil and transmitter coil (k_{01}) is adjusted by changing the lateral alignment of the driver coil using actuator as shown in the figure 13. The coupling between driver coil and receiver coil is very weak, which is neglected in the analysis.

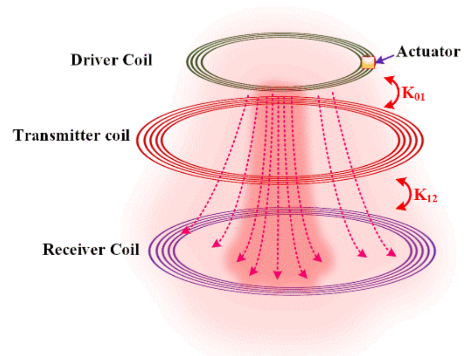


FIGURE 13. Proposed driver coil system.

$$\omega = \frac{1}{\sqrt{L_0C_0}} = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}} \tag{3}$$

$$Z_2 = R_2 + R_L \tag{4}$$

$$Z_1 = R_1 + \frac{(\omega k_{12}\sqrt{L_1L_2})^2}{Z_2} \tag{5}$$

$$Z_0 = R_0 + \frac{(\omega k_{01}\sqrt{L_0L_1})^2}{Z_1} \tag{6}$$

Z_1 (5) is the input impedance without out driver coil, Z_0 (6) is the input impedance with driver coil. K_{12} is the coupling coefficient between transmitter and receiver coils, which cannot be varied in conventional WPT system therefore Z_1 cannot be matched with variable load side impedance Z_2. With proposed WPT system input impedance is varied by adjusting the K_{01} as illustrated in the equation (6). This proposed system is validated with power scaled down prototype of 100 W operating at 150 kHz for the safety reasons and achieved efficiency of around 85%. It has 10 turns, 30 turns and 15 turns for driver coil, transmitter coil and receiver coil respectively. Though it has lesser efficiency than typical WPT system, it suggests the technique for impedance matching [58].

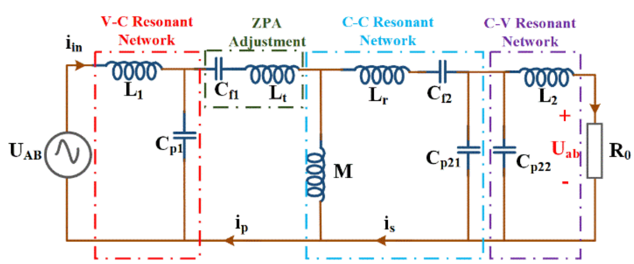


FIGURE 14. Proposed impedance matching using passive element tuning.

3) IMPEDANCE MATCHING USING PASSIVE ELEMENT TUNING IN THE DOUBLE SIDE LCC COMPENSATED WPT SYSTEM

When compared with active impedance matching, the passive impedance matching uses lesser components for impedance matching. The impedance matching is achieved only by tuning the resonant elements of the WPT system. In this method the reflected power due to the mismatch of source side and load side impedance is compensated by tuning the basic resonant components of the system as shown in the figure 14. It analyzed the frequency characteristics, conditions for achieving resonance in the both transmitter and receiver sides for double sided LCC compensated WPT system. Which accomplishes this by optimizing the two compensation parameters α and β corresponds by the inductance of the primary and secondary inductance of the WPT system. The improvement in efficiency with designated operating power at independent constant voltage (CV) as well as zero phase angle (ZPA) were achieved.

$$\alpha \geq \frac{U_{AB}}{\omega_0 L I_{p\max}} \tag{7}$$

$$\beta \geq \frac{1+\alpha\delta L}{\omega_0 \alpha L\sqrt{\left(\frac{I_{S\max}}{U_{ab}}\right)^2-\left(\frac{\alpha\delta L}{R_0}\right)^2}} \tag{8}$$

The equation (7 & 8) gives the expression finding the upper range of the compensation parameters α and β.

$$\alpha < \frac{\beta L - M^2\delta}{\left(M^2\delta^2+\beta\right)L} \tag{9}$$

$$\beta < \delta L \tag{10}$$

Similarly equation (9 & 10) gives the lower range of the compensation parameters, based on this primary (L_1) and secondary (L_2) inductance were tuned to achieve the desired impedance matching with CV and ZPA [90].

The proposed tuning methodology is confirmed with experimental results obtained by using 2kW prototype model. The performances of this system is evaluated with various values for α and β and concludes that at $\alpha = 0.58$ and $\beta = 3.263$ the power transfer efficiency reaches 92.14% at operating power of 1.6 kW. The coupling coefficient is varied from 0.167 to 0.137 the performance is not disturbed with proposed tuning methodology.

4) MISALIGNMENT TOLERANCE IMPROVEMENT USING CAPACITOR TUNING FOR LCC-LCC COMPENSATED WPT SYSTEM

In this article the switched controlled capacitors are used in the primary side of the WPT system. It compares the performance of the tuned capacitor based WPT system with conventional un-tuned WPT system at variation in the coupling coefficient from 0.175 to 0.075. The equivalent circuit of the proposed WPT system is shown in the figure 15, the capacitors from the primary side C_{f1} and C_1 are made with switched capacitor.

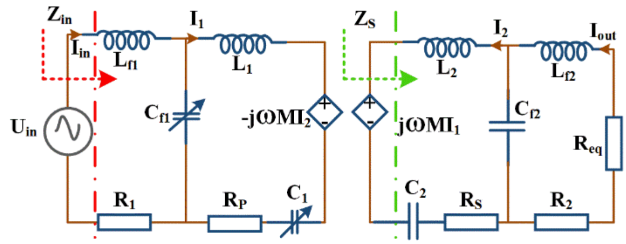


FIGURE 15. Proposed impedance matching using switched controlled capacitor.

Using output current (I_{out}), voltage (U_{out}) and load resistance (R_L) the load side impedance is calculated, which all were sampled and transmitted to the primary side controller. Based on which the switching pulses for the switched capacitor were regulated to match the load impedance and regulates the power transmission efficiency with constant power and zero phase angle. The entire proposed work is validated with scaled down prototype model of rated power 330 W operates at an efficiency of between 88.13 - 88.3% [91].

In WPT systems impedance matching technique is one of the promising technique to optimize the power transfer efficiency. The different methods approached by the researchers were tabulated in the Table 6. In all methods the load impedance were detected, based on it the controller do changes in the source impedance by adding additional coils or variable capacitor banks or variable inductor or repeater coils etc. However, achieving effective impedance matching can be challenging due to the varying impedance of the WPT system. The impedance can fluctuate depending on several factors such as the distance between the transmitting and receiving coils, the alignment of the coils, and the load impedance. As a result, designers faces the challenge of carefully selecting the right components and adjusting the system parameters to ensure that the impedance matching is optimal.

Furthermore, the design and implementation of impedance matching circuits can be expensive. High-quality components such as variable capacitors and inductors are typically required. These components can be costly and can make the system more complex. In addition, the design of the impedance matching circuit should be tailored to the specific WPT system's requirements, which can add to the cost and complexity. Finally, impedance matching may lead to increase of losses in the system. This is because the impedance matching circuit consumes some power, which can reduce the overall efficiency of the WPT system. The power loss is dependent on the type of impedance matching circuit used and the efficiency of the components. In case of EV WPT charging system the range of impedance change is huge when compare to other type of WPT applications. It requires high span variable capacitors and inductors, which may increase overall cost of the system.

TABLE 6. Features and comparison of various impedance matching techniques in WPT system.

Impedance Matching Method	Power Rating	Frequency	Coupling Coefficient	Efficiency
A. Active impedance matching				
1) Active controlled tuning for inductive charging of electric vehicles [85,86]	7 kW	85 kHz	0.1 to 0.2	92.7 %
2) Impedance Mapped compensation network with dual phase shift control [87].	2.2 kW	85 kHz,	0.12 to 0.2	92.3% to 94.3 %
3) Impedance change matched by resonant frequency control [88].	1 kW	75.30 & 82.42 kHz	(Air gap) 5cm, 10cm	98.20 % & 90 %
4) Impedance matching using self-adaptive resonance methodology [89].	250 W	85 kHz	0.192 – 0.302	85%
B. Passive Impedance Matching				
1) Maximization of the efficiency using switched controlled capacitors [58].	6.6 kW	85 kHz	0.3	95.1 %
2) Impedance matching using driver coil [58].	100 W	150 kHz	0.2	85 %
3) Impedance matching using passive element tuning in the Double side LCC compensated WPT system [90].	2 kW	85 kHz	0.137 to 0.167	92.14 %
4) Misalignment tolerance improvement using capacitor tuning for LCC-LCC compensated WPT system [91]	330 W	85 kHz	0.175 to 0.075	88.3 %
5) Variable inductor control for misalignment tolerance [92]	500W	150 kHz	0.085 to 0.174	92.9%

IV. EFFICIENCY IMPROVEMENT BY COMPENSATION TECHNIQUES

In an IWPT system the overall impedance of the couplers are huge, which can significantly reduce the flow of current through the load. One possible solution to the problem is by increasing the input voltage. However, this approach may not ideal since it circulates huge current in the transmitter coil, resulting in huge loss of energy and poor efficiency. Therefore, it is necessary to minimize the impedance of the coils as much as possible, while maximizing their self-inductance, to produce maximum possible flux. The goal is to use coils with the highest possible quality factor. The expression for the quality factor is given in the following expressions (11) & (12) with inductance of primary or transmitter pad (L_{Tr}), inductance of secondary or receiver pad (L_{Rr}), Source resistance (R_S) and Load resistance (R_L), Quality factor of primary coil (Q_T) and secondary or receiver coil (Q_R) [93], [94].

$$Q_T = \frac{\omega L_T}{R_S} \tag{11}$$

$$Q_S = \frac{\omega L_R}{R_L} \tag{12}$$

The quality factor is improved by reducing or even cancelling the high inductive reactance of the coil with inclusion of equivalent capacitive reactance into the circuit. Such technique is called as compensation technique. This phenomenon pertains to the deviation in frequency from the originally intended frequency [95]. One of the main advantages of compensation techniques is that they can help to match the impedance of the coils and provide path for the reactive current to flow, resulting in improved efficient. In addition, compensation techniques can help to reduce the effects of load variations and changes in the distance between the coils, which in turn leads to increased stability of the system. Moreover, they can also help to reduce the electromagnetic interference (EMI) generated by WPT systems. In general charging of EV through wireless mode requires air gap in range of 160mm to 300mm as per SAEJ2954 standard, also for convenience of the EV user, which involves large leakage inductance. It needs to be compensated using a capacitor connected on both sides in series or parallel with transmitter or receiver pad. Also, which resonates in accordance with primary and/or secondary inductance.

One of the fundamental topologies of compensation involves, having one compensating capacitor on both sides it may either series or parallel. These are commonly referred to as classical or basic compensation [92], [94]

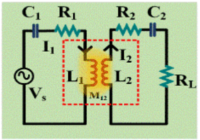
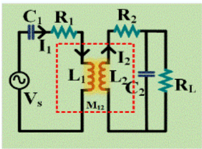
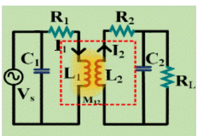
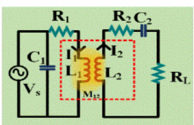
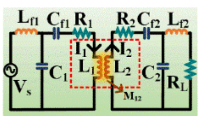
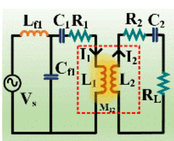
Functions of compensation network,

1. Minimization of VA power rating of the WPT system.
2. Enhancement of PTE.
3. Deliver constant voltage or constant current.
4. Reduced bifurcation phenomenon by zero phase angle (ZPA) output.
5. Reduce the reactive power supply to the grid.

As shown in figure 16, the basic classifications are Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP). In basic compensation two alphabets indicates the pattern of capacitor connection with primary coil and secondary coil respectively. Its basic network topologies and its equivalent impedance and features were illustrated and compared in Table 7.

In many standard applications, SS and SP compensations are utilized due to their high efficiency. One of the key benefits of using SS and SP compensation methods is that

TABLE 7. Comparison of basic Compensation topologies.

Topology	Equivalent Circuit	Features
SS		❖ **Total Impedance (Z_{SS}):** **Voltage Gain (G_{SS}):** $Z_{SS}=\left[R_1+j\left(L_1\omega-\frac{1}{C_1\omega}\right)\right]+\frac{\omega^2M^2}{\left[R_2+R_L+j\left(L_2\omega-\frac{1}{C_2\omega}\right)\right]}$; $G_{SS}=\frac{V_{out}}{V_{in}}=\frac{-j\omega MR_L}{\left[Z_{SS}\left(Z_S+\frac{1}{j\omega C_2}+R_L\right)\right]}$ Z_S & Z_P are total impedance of secondary and primary side network, ❖ For both SS and SP the VA rating is large at input side, the total impedance of the network drops with misalignment. ❖ It ensures efficiency up to 94.6%, Reflected reactance is always zero.
SP		❖ **Total Impedance:** **Voltage Gain (G_{SP}):** $Z_{SP}=\left[R_1+j\left(L_1\omega-\frac{1}{C_1\omega}\right)\right]+\frac{\omega^2M^2}{\left[R_2+jL_2\omega+j\left(\frac{R_L}{1+jR_LC_2\omega}\right)\right]}$; $G_{SP}=\frac{V_{out}}{V_{in}}=\frac{-j\omega M}{\left[Z_{SP}\left(Z_S+\left(j\omega C_2+\frac{1}{R_L}\right)+1\right)\right]}$ ❖ In SP and SS topologies the output voltage and current are independent with load, which facilitates constant current (CC) & constant voltage (CV) modes of charging in EV applications. ❖ It ensures smooth control over variable load conditions, efficiency up to 95%. ❖ Reflected reactance depends on frequency. Both SS and SP compensation topologies are more suitable for EV wireless charging applications.
PP		❖ **Total Impedance:** **Trans impedance Gain(G_{PP}):** $Z_{PP}=\frac{1}{\frac{1}{\frac{1}{(R_1+jL_1\omega)}+\frac{\omega^2M^2}{\left(R_L+(R_2+jL_2\omega)(1+jR_LC_2\omega)\right)}}+jC_1\omega}$; $G_{PP}=\frac{V_{out}}{I_{in}}=\frac{-j\omega MZ_{PP}}{\left[\left(Z_P+\frac{(\omega M)^2}{Z_S}\right)\left(Z_S+\left(j\omega C_2+\frac{1}{R_L}\right)+1\right)\right]}$ ❖ For both PP and PS the VA rating is low at input side, the total impedance of the network increases with misalignment. ❖ Reflected impedance depends on frequency, PP is more suitable of the WPT system which is having higher impedance.
PS		❖ **Total Impedance:** **Trans impedance Gain(G_{PP}):** $Z_{PS}=\frac{1}{(R_1+jL_1\omega)+\frac{\omega^2M^2}{R_2+R_L+j\left(L_2\omega-\frac{1}{C_2}\right)}+jC_1\omega}$; $G_{PS}=\frac{V_{out}}{I_{in}}=\frac{-j\omega MR_LZ_{PS}}{\left[\left(Z_P+\frac{(\omega M)^2}{Z_S}\right)\left(Z_S+\frac{1}{j\omega C_2}+R_L\right)\right]}$ ❖ Reflected impedance is always zero. ❖ Output voltage is independent of load variations but the current varies with load, hence it is not more suitable EV charging applications.
LCC-LCC		❖ **Total Impedance:** **Trans impedance Gain(G_{PP}):** $Z_{LCC}=jL_{f1}\omega+\left(jC_{f1}\omega+\left(jL_1\omega-\frac{1}{jC_1\omega}+\frac{(M\omega)^2}{Z_S}\right)^{-1}\right)^{-1}$; $G_{LCC}=\frac{V_{out}}{I_{in}}=\frac{\omega MR_L}{\left[\left(1+C_{f1}\omega\left(\frac{(M\omega)^2}{Z_{sec}}+j\omega L_1-\frac{j}{\omega C_1}\right)\left(1+\omega C_{f1}\left(R_L+j\omega L_{f2}\right)\right)\right)Z_{in}Z_S\right]}$ ❖ It offers efficiency 95% even with poor quality factor (Q). ❖ VA rating is gets reduce further 4% then other compensation topologies, High cost for compensation components.
LCC-S		❖ **Total Impedance:** **Trans impedance Gain(G_{PP}):** $Z_{LCCS}=jL_{f1}\omega+\left(jC_{f1}\omega+\left(jL_1\omega-\frac{1}{jC_1\omega}+\frac{(M\omega)^2}{Z_S}\right)^{-1}\right)^{-1}$; $G_{LCCS}=\frac{V_{out}}{I_{in}}=\frac{\omega MR_L}{\left[\left(1+\omega C_{f1}\left(\frac{(\omega M)^2}{Z_S}+j\omega L_1-\frac{j}{\omega C_1}\right)\right)Z_{in}Z_S\right]}$

the capacitance value remains constant even when there are variations in the load. Additionally, for SS compensation, the primary capacitance is not dependent on the coupling coefficient. This features are more suitable for multi-coil based WPT system. The remaining two basic topologies are PP and PS compensation methods, which are requires to driven by current source inverter. In contrast to SS and SP compensation methods, the capacitance values in PP and PS depends only both the coupling coefficient and the load resistance. Additionally, PP topology typically requires a

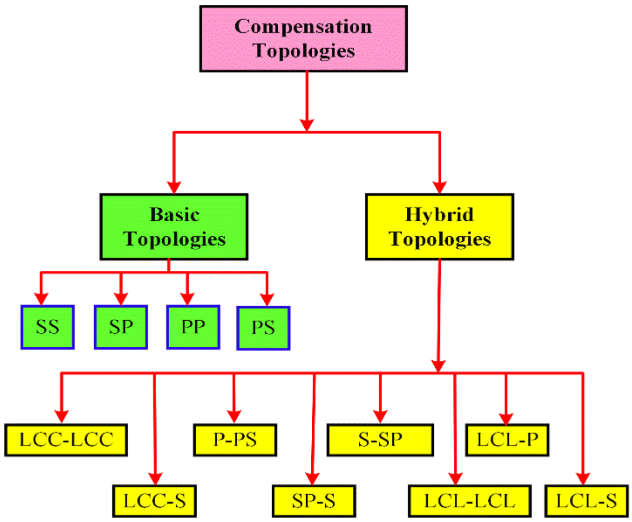


FIGURE 16. Classification of compensation topologies for WPT system.

high value of transmitter side capacitance value than required capacitance for PS topology [96].

The efficiency of the WPT system can be further improved by operating the inverter with zero voltage switching (ZVS) and zero current switching (ZCS). Therefore, zero phase angle between voltage and current is necessary, this can happen only with proper designing of compensation parameters for particular loading and transmission distance [97], [98].

The basic compensation topologies are typically designed for ideal conditions. Unfortunately, factors like misalignment and frequency deviation can make it difficult for WPT applications to function properly. To overcome these challenges, multiple elements can be used in series-parallel combinations to create more effective compensation methods. Which includes integrated basic topologies such as P-PS, SP-S, and S-SP [93].

In addition to this multiple component compensations were also used to improve the features like harmonic suppressing, constant voltage, constant current, voltage regulation, cost minimization, etc. There are many combination of compensating elements, in which some of them were listed in figure 17 (a-f) such as double sided LCC [99], LCL [100], [101], and integrated LCC [50].

In [99] article presents a double-sided Inductor-Inductor-Capacitor (LCC) compensation, and concludes that the resonant condition is independent of loading condition and coupling coefficient. Such, type of compensation is more suitable for the WPT applications were the coupling coefficient is often changes, which improves the tolerance for misalignment in WPT systems. Therefore it is more suitable for dynamic and quasi-dynamic WPT charging system of an EV. In [50], also presented the WPT system with LCC topology with various current circulating modes. It has similar characteristics to the LCL compensation such as improvement in efficiency, reduction in mass as well as cost.

In [101] author involved a comparison of various topologies of compensation with LCL type, such as LCL-P,

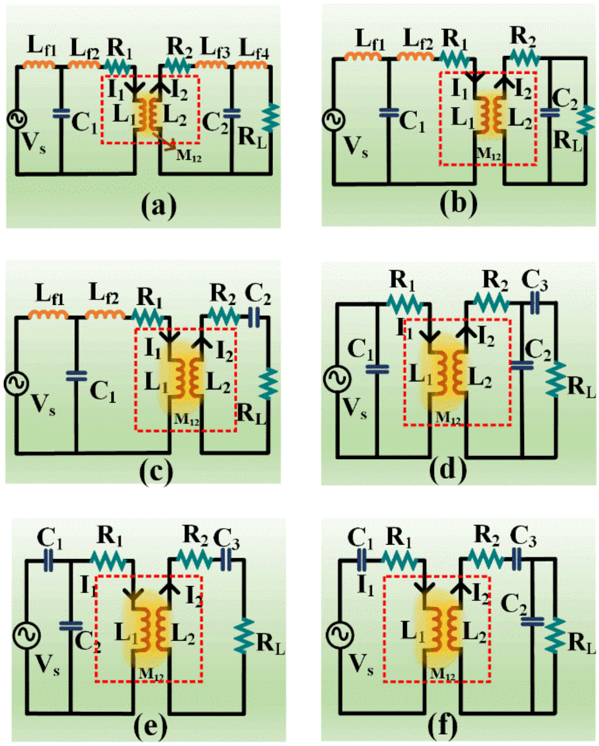


FIGURE 17. LCL-LCL b. LCL-P c. LCL-S d. P-PS e. SP-S f. S-SP.

LCL-S, and LCL dual side. The author analyzed the load characteristics of these topologies and observed that they exhibited similar characteristics to LCC. However, the authors cautioned against the use of LCL-S in situations that may lead to a short circuit as it may result in a high level of secondary side current, which is undesirable.

For the better understanding the characteristics of the fundamental compensation topologies, (SS, SP, PP, PS) a petal diagram Figure 18 has been constructed based on the results analyzed in [92], [93], and [102]. In this article author analyzed all type of basic compensation topologies in WPT system which having weak coupling between transmitter and receiver coil with Class-E converter at 1 MHz frequency and suggested the SS topology offers highest efficiency.

Multi-coil based WPT system is recently concentrated by researchers to enhance the PTE and misalignment tolerance. Which adds additional complexity in compensation network, based on these configuration the compensation systems are called categorized as follows Multi Input- Single Output (MISO) System, Single Input-Multi Output (SIMO) System, and Multi Input-Multi Output (MIMO) systems. In the realm of multi-coil based WPT systems, the series compensation topology is the preferred choice due to its simplicity in design and analysis, compared to other compensation topologies. This method is practical and efficient, and has been widely adopted in multi-coil based WPT systems. On the other hand, other compensation topologies such as parallel, LLC, and LCL topologies are more complex and have not yet been widely preferred. In [103], [104], and [105] multi-transmitter

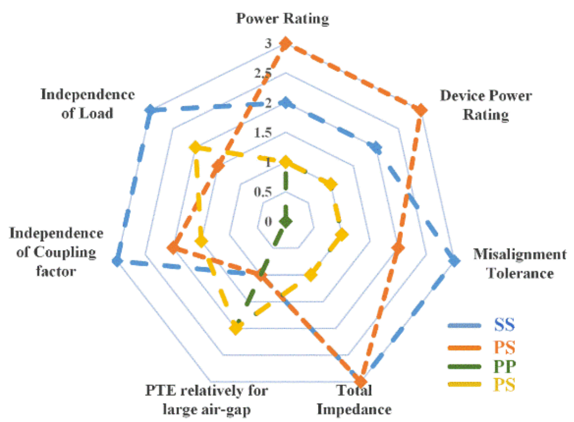


FIGURE 18. Basic compensation topology comparison.

based WPT system with SS compensation were analyzed and achieved the PTE of more than 90%. However, in all cases PTE is affected due to lateral misalignment, which need for in-search of better compensation topologies for multi-coil WPT system. In [106] achieved better efficiency with two in-phase excitation for dual transmitter and single receiver with LCC compensation topology. In [107] reconfigurable LCC compensation were built to perform constant voltage and constant current and achieved an efficiency of more than 95 % in both charging modes.

V. EFFICIENCY IMPROVEMENT BY UNIFORM FLUX DISTRIBUTION USING MULTI-COIL CONFIGURATION

Apparently, the coils are responsible for generating and receiving the electromagnetic field that carries the power. Apart from coil geometry the PTE and transmission distance can be improved by using multiple coils. Which is divided into two structure multiple transmitter coil structure and relay coil structure. However, the control techniques and size may add additional cost to the transmitter side. Latter structure increases the transmission distance by relay coil which occupies space in the transmission path between transmitter and receiver.

A. MULTI-TRANSMITTER COIL APPROACH

The multi-transmitter based WPT system is the promising approach to accomplish the improvement in the misalignment tolerance. Depending on the required misalignment tolerance the number of transmitters is decided. The selection of the optimal transmitter coil to achieve maximum efficiency is challenging, which involves adapting efficient technique to detect the position of the receiver coil.

1) DUAL PHASE COPLANAR TRANSMITTER BASED WPT SYSTEM

The conventional single coil transmitter is replaced with dual phase coplanar transmitter, two coils were wound coaxially with 2mm air gap between them as depicted in the figure 19b. The operation of the WPT system accomplished for charging the EV battery with proposed coplanar transmitter and single receiver. The both transmitter coil were stimulated with two different inverter outputs powered from single source as illustrated in figure 19a, such that both outputs are at slight phase shift between them to minimize the effect of cross coupling. The inclusion of additional coil improves the efficiency of the WPT system up to 91 % on transmitting more 300 W of power from source to battery. Moreover, which also improves misalignment tolerance by employing reconfigurable LCC compensation topology [108].

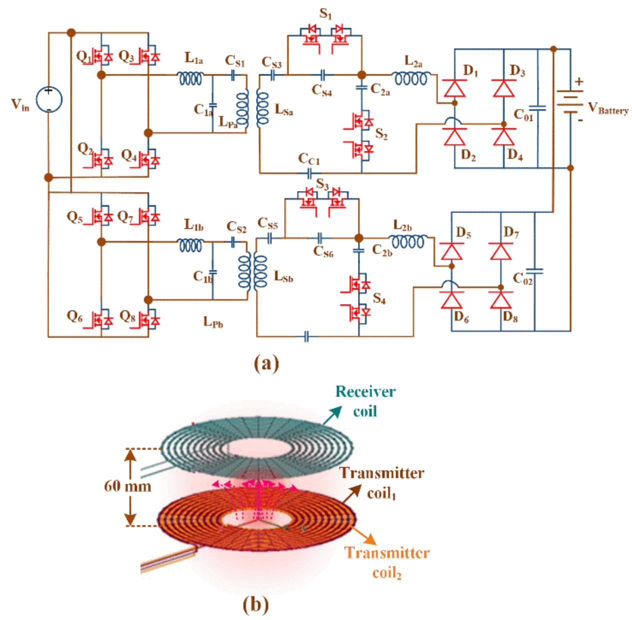


FIGURE 19. a) Circuit configuration of LCC compensated dual phase coplanar transmitter b) Coil geometry and structure of coplanar coil.

The two phase WPT system circuit topology is show in figure 19a, which utilized separate full bridge inverter for exciting the two coils and as well as used separate full bridge rectifier. The two-phase parallel topology is superior alternative to the single-phase topology due to its ability to provide the same output power with an extended air gap distance. This feature enhances the performances of the system, making it more reliable and efficient.

The reconfigurable LCC compensation topology were used to charge the battery in two different modes such as CC and CV. This proposed WPT system concludes that the efficiency were improved during both CC and CV modes of operation by 3 % and 2 % respectively.

2) TWO-TRANSMITTER BASED WPT SYSTEM FOR THE ENHANCEMENT OF PTE

In WPT system the promising issue which needs to be addressed is misalignment, the most prominent solution is by using multi-transmitter. The impedance mismatch due to misalignment is matched by sensing the impedance deviation and excite the adjacent transmitter coils, which is accomplished by proposed dual closed loop method. The first closed loop generates the pulse to control the inverter to match the deviated impedance due to misalignment and second loop generates the pulse to control the DC-DC converter to buck or boost the power transfer to the battery. The proposed system is validated with, 500 W prototype model which exhibits improvement in efficiency rate of above 90 % even with misalignment of 0-40% of coils size. Concludes that the proposed system achieves improvement in efficiency of around 20 % than conventional system with 40 % lateral misalignment [109], [110].

Figure 20. Shows the inverter setup for multi-transmitter, using this author has analyzed the mutual inductance variations with considering two transmitter model. In prototype full-bridge inverter built with SiC based MOSFET switch, which excites the two transmitter pad and single receiver pad with dimensions of 24.1 × 20 cm with vertical distance of 50mm. The power transfer capability is verified with lateral misalignment of 0 to 14 cm for which system always maintains the PTE of 90 % and above.

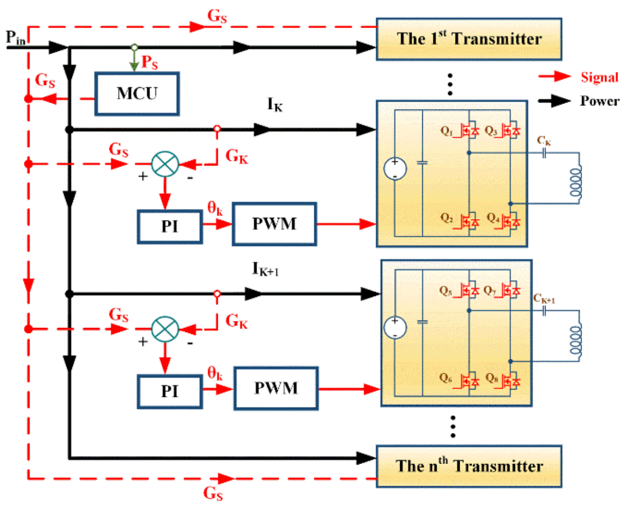


FIGURE 20. Transmitter side inverter setup for multi-transmitter.

3) OPTIMAL STIMULATION OF MULTIPLE TRANSMITTER BASED WPT SYSTEM

In case of multiple transmitter based WPT system the proper excitation of the particular coil which has better coupling with receiver coil is necessary. In this work author suggested an efficient method for exciting the proper coil, which has significant impact on power transfer efficiency as well as misalignment tolerance. The proposed method is based on identifying the coils which exhibits weak coupling with receiver coil. The weak coupling is identified by sensing the transmitter coil current, if the coefficient of coupling is greater than 0.414 times of ideal coefficient of coupling, then it considered for excitation. The coefficient of coupling is obtained by comparing the ratios of transmitter currents, since the ratios of coefficient of coupling between adjacent coils is equal to the ratios of corresponding current circulating through the coils [106].

The circuit configuration of LCC compensated inverter for multi transmitter WPT system is shown in figure 21. The LCC compensation maintains the resonant frequency independently even with changes in the load impedance. In a transmitter array with two coils, the coils are laid out with geometrical Overlap to remove null points, causing intra-coupling between the coils. This intra- coupling alters the transmitter resonance frequency but the impact of different coils currents on the inverter is not analyzed in this article. The proposed methodology has validated with prototype model and achieved the efficiency of 84 % which also concludes that the ratio between the current of adjacent coil is equal to the ratio of their coefficient of coupling.

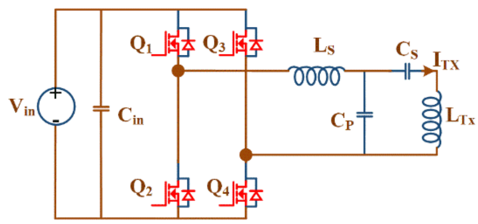


FIGURE 21. LCC compensated resonant inverter.

4) RECONFIGURABLE DUAL-TRANSMITTER BASED IMPROVED MISALIGNMENT TOLERANCE

In WPT system series-series compensation is most prominent topologies to improve the power transfer efficiency. However, the variation of the load impedance due to misalignment may cause reduction of transfer efficiency. Here author proposed a reconfigurable compensation topologies for dual transmitter, based on the position of the receiver coil compensation is configured to either SS or LCCC-S. When the receiver coil is positioned at the middle section over the dual transmitter, the control switch (C_F) is in 'OFF' condition and system operates at S-S compensation, which transfers maximum power to receiver coil. When the receiver coil is positioned at either end of the dual transmitter then which affects the power transfer capability of the system. The power transfer is improved by operating the WPT system with LCCC-S compensation topology by making the CF 'ON'. With additional components the loss is compensated and balanced the power transfer of the system even at misalignment condition. This feature enables the system to maintain stable output power even when the misalignment increases, thus improving the system's performance [107].

The circuit configuration to reconfigure SS and LCCC-S is shown in the figure 22. The relay switch CF is the control switch to change the compensation topology. The proposed configuration is validated with experimental setup with overall dual-transmitter coil dimension of 600 X 300mm and receiver coil dimension of 300 X 300mm. The balance output is achieved at 500mm vertical misalignment and 100 mm horizontal misalignment. During this operation the efficiency is varying between 90 – 95 %.

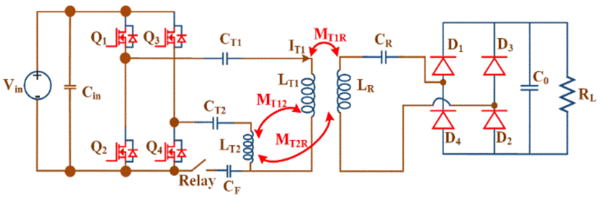


FIGURE 22. Circuit configuration with reconfigurable compensation.

5) WPT SYSTEM WITH UNIPOLAR DUAL COIL TRANSMITTER

In this paper, a comprehensive study of a novel IWPT system is presented, which is designed to address the challenges of misalignment performance, stability of output power, and short circuit as well as open circuit fault tolerance. Two unipolar coil were used in the transmitter among them one is acting as main coil and another one acts as compensation coil. Both coils involves the power transmission, the novelty in this proposed system is that the coils were creates opposite effects on the receiver coil. This feature enables the system to maintain stable output power even when the misalignment increases, thus improving the system's performance. Also the fault analysis were made for the system and concludes that the stability of the system is improved even with open circuit and short circuit fault [111].

The circuit configuration is shown in the figure 23. L_t and L_r were inductance of transmitter and receiver coils respectively, L_f is the compensation inductance. C_r and C_1 are primary side compensation capacitance and C_2 is secondary side compensation capacitance. U_{Bus}, U_1, U_2 and U_{bat} are voltages of input supply bus, inverter output, rectifier input and output respectively. The prototype built for the system has been tested and verified for the validation of the proposed system. Which is made to charge battery of voltage 48V, 16 Ah, due to the misalignment occurring in the range of 0 mm to 90mm, the DC output power varies between 297 to 321 W, in the meantime the efficiency achieved in the range of 9.78 % to 93.56 %.

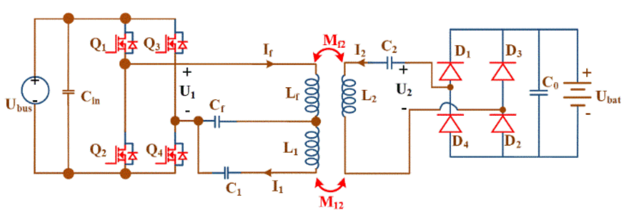


FIGURE 23. Circuit configuration of WPT system with dual unipolar transmitter.

6) THREE COIL WPT SYSTEM WITH LARGE LATERAL MISALIGNMENT TOLERANCE

In this article the IWPT system for EV charging has been enhanced with the transmitter with three independent coil such that all are not magnetically coupled. For improving the lateral misalignment tolerance the three rectangular coils were arranged in such a manner and achieved tolerance up to 20cm. To optimize the system, a current distribution method is used among the three overlapping rectangular coils to reduce coil loss and leakage flux. It can minimize the leakage flux approximately 40%, when compare to other excitation methods. This system also uses a compensation strategy that provides in-phase output which facilitates the use of single capacitor. This is a significant improvement over traditional system, which required different compensators for different coil. This compatibility allows the system to half the cost of the compensation [103].

The proposed current optimization method for three coil transmitter is validated with 3.3 kW WPT system. The transmitter and receiver coils were separated with the distance of 200 mm the transmission efficiency is reaches up to 92.9% when at zero misalignment, which decreases to 90.5% when at misalignment of receiver pad with transmitter pad by 20 cm.

The circuit configuration of proposed multi-coil WPT system is depicted in Figure 24. The required high frequency input voltage for the transmitter is produced by three phase VSI (Voltage Source Inverter). The one end terminal of the each coils of three transmitter coil is connected to the point A, B, and C as shown in the figure 24, other end of all the coils were interconnected and connected to the negative terminal of the DC source, such that which form like star connected transmitter coil. A significant advantage of this arrangement is that it allows for independent control of input voltage as well as its phase angle of each coil. However, when this topology is employed, Fourier analysis reveals the existence of a DC-offset between each phase voltage. This DC offset can cause problems in the system and needs to be blocked to ensure proper operation. The series compensation capacitors C1-C3 serve this purpose by blocking the DC offset component. In addition to this function, the capacitors also serve as AC coupling capacitors and compensate for the inductive reactance of the transmitter coils. Thus, the series compensation capacitors play a dual role in the system by blocking the DC offset and compensating for the inductive reactance of the coils. Without these capacitors, the system would not function properly, and the PTE would be severely impacted.

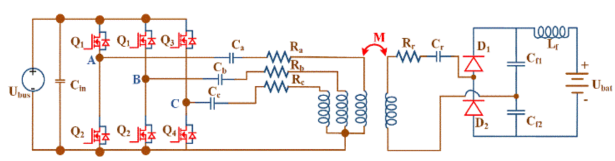


FIGURE 24. Circuit configuration of three transmitter coil WPT topology.

7) FOUR COIL TRANSMITTER BASED WPT SYSTEM WITH REDUCED SWITCH INVERTER

This article highlights the advantages of Multi-coil IWPT systems. The multi-coil IWPT system has several noteworthy advantages when compared to conventional two-coil WPT systems.

It offers improved power transfer efficiency and larger working area, making it a promising solution for future WPT systems. In this research article used a four overlapped coil as shown in the figure 25, as transmitter all were decoupled unipolar coils. The improvement of the misalignment tolerance is increased by optimal excitation of the corresponding coil which is maximum aligned with receiver. It requires independent control of the each coil, which involves power electronic converters with minimum of $2n$ number switches, where 'n' denotes the number of transmitter coils. In this work author proposed an inverter with n+1 switches, not only which minimizing the switches also which have independent control over the excitation. This paper also presents new technique to excite the transmitter coil optimally by sensing and comparing the current circulating in the each coil [104].

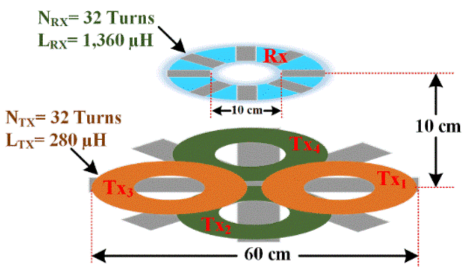


FIGURE 25. Four coil transmitter with single receiver.

The proposed inverter topology for four coil transmitter and optimal coil detection for excitation were validated with 500 W prototype WPT system. The overall diameter of the transmitter coil is 2 feet operated with single receiver coil at an air gap of 100 mm. With coil selection the proposed system achieves 90% efficiency with lateral misalignment of 20 cm. Overall, this research demonstrates the potential of the proposed inverter topology and detection method to simplify WPT systems, reduce component count, and improves PTE.

8) ENHANCEMENT OF MISALIGNMENT TOLERANCE WITH FIVE COIL TRANSMITTER AND SINGLE RECEIVER

In this article, author proposed a novel IWPT system is presented that employs five transmitter coils and single receiver coil. The primary objective of the proposed WPT system is to enhance the efficiency by improving the misalignment tolerance of the conventional single transmitter and receiver based WPT system. The study validates the feasibility of the system through obtained values of the coupling coefficient with misalignment. Compared to the single transmitter coupled coil, the proposed system offers an increased working area, moreover, the power transfer efficiency of the system is enhanced even with lateral misalignment [105].

The proposed five-coil transmitter with single coil receiver coil system offers a promising solution for inductive power transfer applications, providing increased efficiency and working area, making it a valuable contribution to the field. In practical the proposed multi-coil system includes four additional coils compared to the conventional single transmitter and receiver coils have identical dimensions of inner radius 3.5 cm and outer radius 7.5 cm, respectively, and the overall transmission are of the transmitter coil is about 1 square feet as shown in figure 26. The transmitter coils are energized to maximize magnetic coupling for the best possible energy transfer. During operation, the system determines the transmitter coil to excite based on the alignment of the receiver coil. The coil at the center is always in active state, the remaining coils are excited based on the misalignment of the receiver coil, if the receiver coil laterally deviates towards any one of the remaining coils (Coil-2, 3, 4, 5) then that coil also in active state. This novel multi-coil transmitter based WPT system is validated with the prototype model rated of 500 W system and achieved an efficiency of 84 % with 10 cm lateral misalignment.

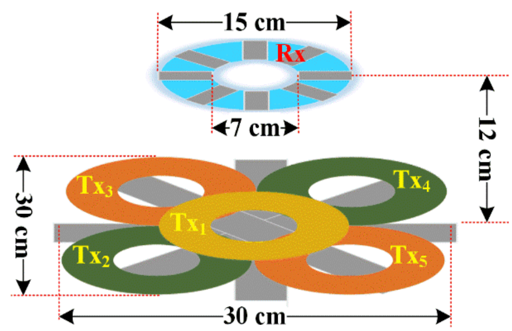


FIGURE 26. Five coil transmitter for misalignment tolerance enhancement.

9) IWPT SYSTEM WITH MULTI (SEVEN) TRANSMITTER AND SINGLE RECEIVER

In this research article, a new approach is presented for selecting transmitter coils in a WPT system. The proposed methodology has been tested on the WPT system with seven transmitter coils and a single receiver coil. The primary objective of the proposed method is to transfer power from the transmitter coil to the receiver coil efficiently to achieve maximum power transfer efficiency. To this end, the proposed method consists of two primary steps. The first step involves deriving the transmitter coil selection criteria by analyzing the value of coefficient of coupling in between adjacent transmitter coil. This criterion is used to stimulate the combination of transmitter coil that can achieve maximum efficiency. The second step involves the detecting the value of coefficient of coupling that can be used to set the criterion for the previous step. Author has presented a method that can calculate the value of coefficient of coupling even the neighbor coils are not in stimulated condition, this feature making this method unique from previous methods.

The proposed method allows selecting the proper combination coils for the stimulation without prior knowledge of the features of receiver coil. This feature makes it highly useful in practical applications. This article followed a systematic approach shown in Figure 27 to derive the optimal transmitter coil combination. The proposed transmitter coil selection criteria is validated in a prototype model of 300 W power and reached the maximum efficiency of 96.5%. Furthermore, the results obtained with this method has an error of 2.5 % when compared to the values obtained using vector network analyzer [112], [113].

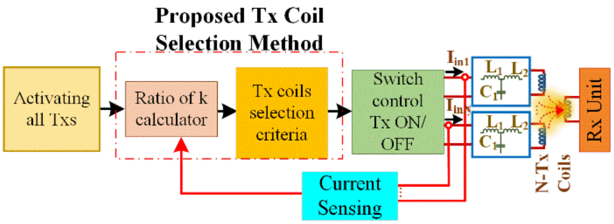


FIGURE 27. Block diagram of transmitter coil selection for optimal stimulation.

After carrying out a comprehensive survey of research articles on efficiency enhancement using multi-transmitter based WPT systems, it can be concluded that these systems have achieved an efficiency of over 90% in all topologies. In [114] the controller is designed for achieving maximum power transfer in multi-transmitter based WPT system.

To provide insight into the different topologies and their operating conditions, table 8 presents a detailed comparative analysis of various multi-transmitter based WPT systems with different power ratings. Regarding compensation, primary sided LCC compensation is found to offer more advantages than series-capacitor compensation. It provides independence of the coupling factor with variations in load, reduces component size, and facilitates both CC and CV mode of charging. This compensation technique is particularly useful when developing multi-transmitter based WPT systems. However, it is essential to remember that the PTE of the WPT system is significantly reduced when there is 0 to 35% lateral or angular misalignment on the overall dimensions of the transmitter pad. Also, optimal selection of the transmitter for stimulation based on the alignment with the receiver coil adds extra complexity to the system.

In summary, this survey has shown that multi-transmitter based WPT systems are highly efficient, and primary sided LCC compensation is the preferred compensation technique. However, it is crucial to be aware of the limitations of the system, such as reduced efficiency in case of misalignment and the complexity of optimal transmitter selection.

B. EFFICIENCY IMPROVEMENT USING RELAY OR RESONATOR COIL

In a WPT system, single transmitter coil and single receiver coil is used to create an electromagnetic field that transfers power from the transmitter side to the receiver side. The efficiency of the WPT system mainly affected by the air gap distance between the transmitter and receiver coils and the condition of misalignment of the coils. If the coils are too far apart or not aligned properly, the PTE of the system will be reduced. A relay coil can be used to improve the effectiveness of a wireless power transfer system by acting as a booster coil. The relay coil is always situated in between the transmitter and the receiver coil. When the transmitter coil is energized, the magnetic field around this coil that induces a circulating current in the relay coil. The circulating current in the relay coil which creates a magnetic field that is stronger than the field which was created by the transmitter coil. This stronger magnetic field is then creates circulating current in receiver coil effectively, thus the power is effectively transferred to the receiver coil, which improves the PTE of the system. In addition to improving efficiency, a relay coil can also be utilized to extend the air-gap distance of a wireless power transfer system. The relay coil can be placed closer to the transmitter coil, which increases the strength of the magnetic field that is transferred to the receiver coil. This allows the receiver coil to be placed further away from the transmitter coil, which extends the range of the system. Relay coils are a valuable tool for enhancing the PTE and air-gap distance between the transmitter and receiver coils of the WPT systems. By understanding how relay coils work, we can use them to design wireless power transfer systems that are more efficient and effective.

Here are some of the benefits of using relay coils in wireless power transfer:

Improved Efficiency: Relay coils can help to enhancing the PTE of WPT systems by boosting the generated flux that is transferred to the receiver coil. This can lead to significant savings in power consumption.

Extended Range: Relay coils can also help to extend the range of wireless power transfer systems by placing the relay coil closer to the transmitter coil. This allows the receiver coil to be placed further away from the transmitter coil, which can be useful in applications where the transmitter and receiver coils cannot be placed close together.

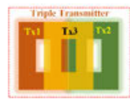
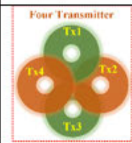
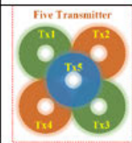
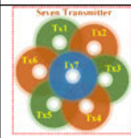
Reduced Complexity: Relay coils can help to reduce the complexity of wireless power transfer systems by eliminating the need for complex power electronics. This can make wireless power transfer systems more affordable and easier to deploy.

Overall, relay coils are a valuable tool for enhancing the PTE, range, and complexity of WPT systems. By understanding how relay coils work, you can use them to design wireless power transfer systems that are more efficient, effective, and affordable.

1) ENHANCEMENT OF TRANSMISSION EFFICIENCY BASED ON SINGLE RELAY RESONATOR IN A WPT SYSTEM

With article [115], [116] provides a comprehensive analysis of the WPT systems with single intermediate coil. Also which guides the design procedure for intermediate coil based WPT system. The WPT system employs a two-coil structure with a low coupling coefficient, which is compensated by the intermediate coil. The intermediate coil boosts the apparent self-inductance and magnetizing inductance of the primary

TABLE 8. Comparison of multi-Transmitter WPT system [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113].

Parameter	Two transmitter coil based WPT System				Three Transmitter coil based WPT System	Four Transmitter coil based WPT System	Five Transmitter coil based WPT System	Seven Transmitter coil based WPT system
	[109,110]	[106,108]	[107]	[111]	[103]	[104]	[105]	[112,113]
Power	500W	100W	1.5kW	321W	3.3kW	500W	100W	300W
Frequency	90kHz	300kHz	85kHz	85kHz	85kHz	60kHz	65kHz	85kHz
Coupler	Square	Circular	Square	Square	Rectangular	Circular	Circular	Circular
Coil Arrangement								
Air gap Distance	5 cm	5.8cm	10cm	8cm	20cm	10cm	5cm	6.5cm
Compensation	S-S	LCC-S	LCCC-S	LCC-S	S-S	S-S	S-S	LCC-S
Efficiency	90%	83%	95%	93.56%	92.27%	90%	90.4%	96.5%
Inverter type	Full bridge inverter	LCC resonant inverter	Full bridge inverter	Full bridge inverter	Full bridge inverter	Resonant inverter	Full bridge inverter	Full bridge inverter
Tx coil selection method	N/A	Current sensing	N/A	N/A	N/A	Current sensing	Current sensing	Current sensing
Misalignment Tolerance	41%	38%	20%	45%	66%	66%	40%	N/A

side while maintaining the apparent coupling coefficient. The analysis includes the derivation of the expression for transfer function and discussion which highlights the importance of the intermediate coil in terms of PTE. This method uses the concept of dual resonance frequency which occurred in a phenomenon called bifurcation. The methodology provides a step by step procedure that guarantee the high power transfer between the transmitter and the receiver coil. The bifurcation phenomenon is induced by the coupling coefficient and significantly improves the efficiency of the system. The proposed design procedure ensures optimal operation of the WPT system and takes into account the different parameters that affect the system's performance.

The entire analysis were validated and verified with prototype model of output power of 6.6kW operating with 100 k Hz and 2000 mm air gap. Which achieved the overall DC to DC PTE of 95.57 %

The WPT system with single intermediate coil is depicted in figure 28. As previously discussed, the intermediate coil plays a crucial role in the system by enhancing the apparent coupling coefficient between the primary and secondary coils. This boost in efficiency induces the bifurcation phenomenon. This article proposes a design method that operates at approximately the second resonance frequency, $\omega 2$, which has a low fundamental approximation error. This is in contrast to the conventional method, which operates at around $\omega 3$. The advantage of this design method is that it offers expected voltage with maximum possible PTE. It is crucial to consider that an intermediate coil in a design can add complexity to the system. Therefore, it becomes imperative to follow step by step procedure to ensure that the intermediate coil is optimized for the intended application.

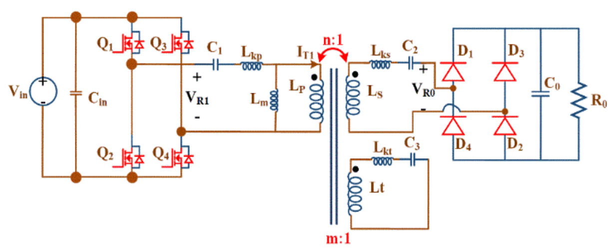


FIGURE 28. Circuit configuration of WPT system with single intermediate coil.

2) WPT SYSTEM WITH SINGLE RESONATOR FOR THE IMPROVEMENT OF PTE

The article [117] provides an in-depth analysis of a three-coil structure WPT system that uses S/S/P compensation to accomplish CC and CV modes of charging at dual ZPA frequencies. It also provides the detailed design procedure and analysis while the system accomplishing CC and CV modes of charging. Moreover, it analyses the suitability of the compensation parameters to CC and CV performance, which is crucial in optimizing the performance of the WPT system.

In addition to the theoretical analysis, the article introduces the employment of ZVS to the system performance which improves the PTE further. The proposed system achieves a charging current of 4.6A and a charging voltage of 56 V, as demonstrated by the experimental results are consistent with the theoretical analysis, validating the effectiveness of the proposed design.

The WPT system proposed in this study comprises of various components, including the DC input voltage source U_d, full-bridge rectifier, and battery load. The resonant tank is made up of the source coil *Lp*, transmitter coil L_t, and receiver coil *Ls*, along with additional compensation capacitors and resistors. The full-bridge high frequency inverter consists of four power MOSFETs (*Q1-Q4*), while the full-bridge rectifier has four Schottky diodes (*D1-D4*) that are used to power the battery load R_L. This three coil structure WPT system is illustrated in figure 29.

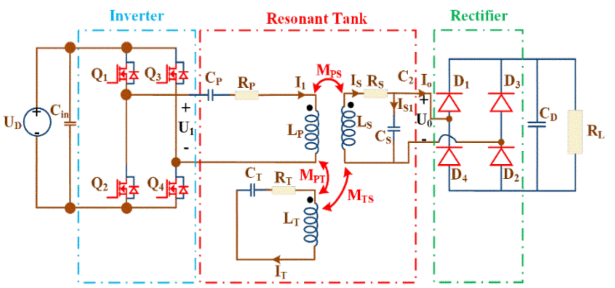


FIGURE 29. Circuit configuration the S/S/P three-coil WPT system.

Furthermore, the article compares the performance of this proposed system with conventional systems of this same type, and highlighting the superiority of the proposed three-coil structure WPT system. The proposed system offers several advantages, including a compact and portable receiver, expected voltage with maximum possible PTE, and the ability to accomplish CC and CV modes of charging at two different zero phase angle frequencies. This design method provides a valuable contribution to the field of WPT systems and can be used as a guideline for future research and development in this area.

3) SINGLE AND DUAL RESONATOR BASED WPT SYSTEM

The article [118] compares the energy efficiency of two-coil and three-coil WPT systems based on circuit analysis. The simplified models for both systems were obtained, which facilitates the comparative analysis in terms of energy transfer. To provide a comprehensive analysis of energy efficiency differences between the two structures, simplified circuit models of both systems are proposed. These models allow for an intuitive understanding of the underlying physics of WPT and enable the derivation of an equation that indicates when a three-coil structure is more energy-efficient that its two-coil counterpart. According to the analysis, a properly designed three-coil system can achieve a higher level of power transfer with variation in the load.

This is due to the three-coil system's unique structural advantages, such as its ability to distribution of the current burden and reduction of leakage flux due to misalignment. The whole analysis is validated through simulation and with prototype model, which confirm that the three-coil structure is capable of significantly improving the energy efficiency of WPT systems. This research provides valuable insights for the development of more efficient WPT systems, which could have a significant impact on the design of future wireless charging technologies.

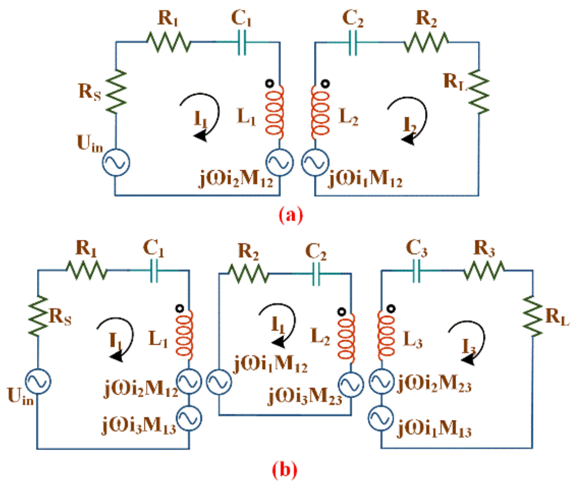


FIGURE 30. a) Equivalent circuit of two coil WPT system b) Equivalent circuit of three coil WPT system.

The two structures can be represented by equivalent circuits, as shown in figure 30. By using basic circuit analysis the expression for efficiency of two and three coil WPT system were obtained as given the equation (13) and (14).

$$\eta_{2C} = \frac{P_o^{2C}}{P_i^{2C}} = \frac{1}{a_{2C}R_L + \frac{b_{2C}}{R_L} + C_{2C}} \tag{13}$$

$$\eta_{3C} = \frac{P_o^{3C}}{P_i^{3C}} = \frac{1}{a_{3C}R_L + \frac{b_{3C}}{R_L} + C_{3C}} \tag{14}$$

According to the results presented in figure 31, the energy efficiency measurements obtained through experimental setup and simulations match well even with variations in the loads up to 20Ω. Also concludes that the transfer efficiency of three coil system is always superior to two coil system. Placing the source coil near to the primary coil is crucial, and which beneficial when primary coil and secondary coil have weak coupling.

4) ASYMMETRIC DUAL RESONATOR WPT SYSTEM

In [119] introduces a new wireless power transfer system that utilizes an innovative asymmetric four-coil resonator to achieve higher efficiency. The proposed system offers a longer transfer distance (*200mm*), operating frequency (*90kHz*), and better coupling coefficient (k), without intermediate coil *k=0.284* while with intermediate coil *k=0.6* that

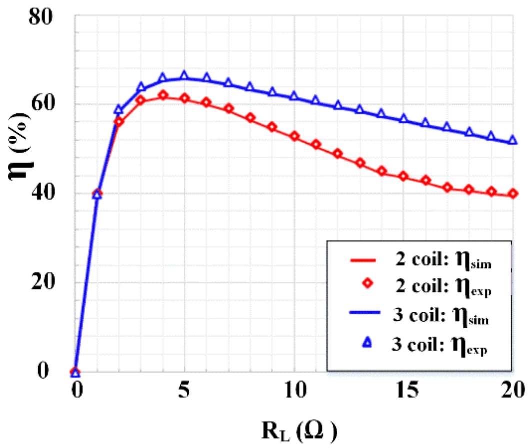


FIGURE 31. Theoretical and practical Efficiency curve of two and three coil WPT system at various loading conditions.

traditional four-coil systems, making it a promising solution for various wireless power transfer applications. Unlike conventional four- coil systems, which have a symmetric coil configuration, the proposed four-coil system has two intermittent coil placed in same plane of the source coil serving as transmitter and single load coil serving as receiver, which is shown in the figure 32. This configuration is designed to enhance the apparent coupling coefficient, leading to improved efficiency compared to the conventional system. This presents a theoretical analysis of the proposed system, including an optimal design method for the resonator. The analysis shows that the proposed asymmetric dual resonator WPT system transfers the energy effectively than the WPT system with intermittent coil placed in between the source and load coil.

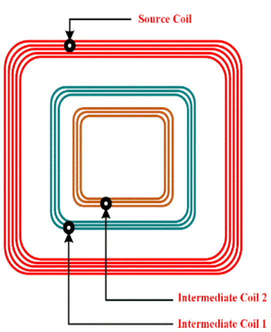


FIGURE 32. Asymmetric four-coil resonator configuration.

The system comprised of a source coil and two intermediate coils on the primary side and a load coil on the secondary side, as depicted in figure 32. The source coil and intermediate coils are arranged on the same plane to maximize the transfer efficiency. Each intermediate coil is equipped with a resonance capacitor that resonates with the coil, although this is not shown in the figure for convenience purpose. The proposed WPT system is designed to improve power transfer efficiency through two different ways. The first involves the double boosting effect due to intermittent coil, which resulting in decreasing the equivalent resistance of the coil. Secondly, the double boosting effect leads to a significant increase in coefficient of coupling at resonant frequency. This increase in coefficient of coupling reduces the current circulation in the primary side, which leads to a reduction in the RMS input current.

To verify the validity of the proposed system, a prototype is implemented to transfers 3.3 kW of power at a switching frequency of 90 kHz and has the air gap distance of 200 mm between the source and load coil. In the experiments, the system achieves an overall PTE of 96.56%, which is a significant improvement over traditional systems. This article concludes that the proposed system has a great potential for various wireless power transfer applications, especially in situations where long transfer distances and high efficiency are required. The theoretical analysis, optimal design method, and experimental results presented in this article.

5) EFFICIENT WPT SYSTEM WITH DUAL INTERMEDIATE COILS

This article [120] presents a new WPT system designed specifically for on-board chargers of electric vehicles, with a focus on high efficiency. The proposed system incorporates two additional intermediate coils with resonant capacitors to enhance the effective magnetizing impedance between the transmitter and receiver coils. This design approach decrease the complex as well as cost of the entire WPT system by eliminating the usage of the ferrite core. Moreover the compensation network of the system can make the converter to acts as voltage source with particular frequency and acts as current source with another particular frequency. Such operation facilitates the converter to charge the battery in both CC & CV mode. The soft switching of converter resulting in zero phase angle output, which is critical for achieving high efficiency.

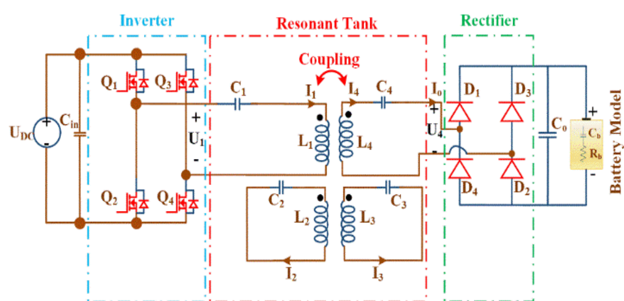


FIGURE 33. Circuit configuration of four coil WPT system.

As shown in figure 33, the proposed high efficiency IWPT system for electric vehicle on-board chargers adopts two intermediate coils to significantly increase the operational impedance of magnetizing, resulting in high-efficiency power transfer. The resonant tank of the converter is designed to operate as a current source for the CC mode charging and as a voltage source for the CV mode charging, and operates at affixed resonant frequency for each charging mode, enabling the zero phase angle condition and full soft switching of all switching devices during the entire charge process. The proposed method is supported by a mathematical model and a detailed design procedure for achieving the zero phase angle condition is also discussed. Moreover, the proposed WPT system is validated using WPT based EV charging system, able to delivers 3.7 kW of power from output side in both CC and CV modes and achieved the power transfer efficiency up to 97.08 %.

6) FOUR COIL WPT SYSTEM WITH IMPROVED MISALIGNMENT TOLERANCE

This article [121] provides a comprehensive and detailed analysis of the design methodology for a practical kilowatt-level WPT system, emphasizing the importance of compensate capacitor optimization. To achieve this the author uses an equivalent circuit model analysis and compares it with the conventional frequency tuning method.

Also investigates the impact of compensating capacitor by analyzing its features. Furthermore, the paper takes into account the specific restrictions and necessities of EV-concerned WPT system, such as safety and efficiency, and presents a thorough optimizing technique and modification criteria. The proposed optimizing method is designed to maximize the transfer efficiency of the WPT system while minimizing the voltages of the transmitter and receiver coils to ensure safety during charging.

The schematic diagram of a basic four- coil coupled magnetically resonates WPT system for EV is shown in figure 34. The proposed system is validated with the 3.3 kW wireless charging prototype, which demonstrates a remarkable transfer efficiency of 92% over 21 cm and 88.5% over 36 cm. the prototype design also achieves balanced and minimized voltages of the transmit and receive coils, ensuring safety and reliability during the EV charging process. Overall, this article provides a comprehensive and detailed analysis of the design methodology for a practical for a practical kilowatt-level WPT system and presents a novel optimizing method that takes into account the unique requirements and constraints of EV-oriented charging systems.

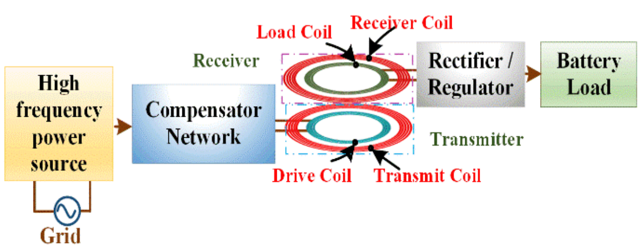


FIGURE 34. Schematic diagram for four coil WPT system.

To provide insight into the different topologies and the operating conditions of WPT system with resonator coils, table 9 presents a detailed comparative analysis of various resonator coil based WPT systems with different power ratings. In summary, this survey has shown that resonator coil based WPT systems are highly efficient, which is around 90% in all topologies. However, it is crucial to be aware of the limitations of the system, such as reduced efficiency in case of misalignment, due to the effect of cross coupling, interference & safety concerns, and power limitations. The relay coil based WPT system may face difficulty when scalability of power is concerned, higher rated power levels may increases the losses due to heating.

VI. FUTURE SCOPE AND RESEARCH GAP

In addition to existing research, the authors hold the belief that further research and development efforts are required to enhance the WPT system performance and overcome the challenges that hinder the technology. The future of WPT looks promising as the technology is expected to become more efficient, powerful, and widely used for several applications in the coming years. In particular for convenient charging of EV, mobile phones, laptops and etc. However, there were several research gaps and challenges in the field of WPT that researchers and engineers were actively working on.

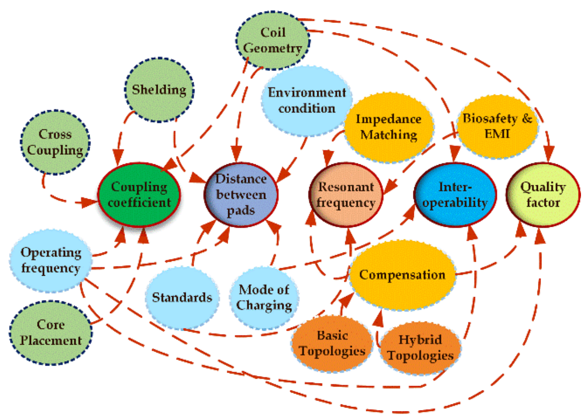
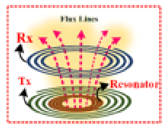
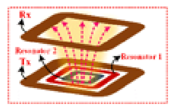
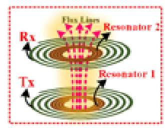
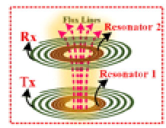


FIGURE 35. Challenging factors in designing high performance WPT system.

Through this review article the identified research gaps, where research is needed in WPT.

- ❖ Increasing the efficiency of WPT systems to minimize energy losses during power transfer.
- ❖ Developing WPT system that can transfer power over longer distances.
- ❖ Ensuring that WPT systems are safe for human beings due to the exposure to electromagnetic fields.
- ❖ Addressing compatibility issues between different WPT technologies and standards.
- ❖ Developing WPT systems that can transfer power to multiple devices simultaneously.
- ❖ It is important to note that these research gaps and challenges may have evolved since then, and new areas of research may have emerged in the field of WPT.
- ❖ Ensure Biosafety by reducing the causes of EMI to human beings as well as communication lines

TABLE 9. Comparison of intermittent resonator coil based WPT system [115], [116], [117], [118], [119], [120], [121].

Parameter	Three coil based WPT System (Single resonator)			Four coil based WPT System (Dual resonator)		
	[115,116]	[117]	[118]	[119]	[120]	[121]
Power	6.6 kW	250W	50 W	3.3kW	3.7 kW	3.3 kW
Frequency	100 kHz	CC- 76.15 kHz CV- 66.35 kHz	684kHz	90 kHz	59.5 kHz	100 kHz
Coupler	Square	Square	Circular	Square	Circular	Square
Coil Arrangement						
Air gap Distance	20 cm	6.5cm	6.2 cm	20cm	20cm	36cm
Compensation	CLL-LC-LC	S-S-P	S-S-S	S-S-S-S	S-S-S-S	S-S-S-S
Efficiency	95.57 %	96%	95%	96.56%	97.08%	92%
Inverter type	Full bridge inverter	LCC resonant inverter	Full bridge inverter	Full bridge inverter	Resonant inverter	Full bridge inverter

As discussed in this review article, there exists multiple techniques that are utilized to improve the PTE. These techniques include impedance matching, compensation topologies, and multi-coil-based WPT systems. The primary goal of each of these techniques is to enhance PTE by focusing on different factor that affect it. Figure 35 provides a visual representation of the various factors that impact PTE and how these techniques target them to improve the overall performance.

VII. CONCLUSION

This paper concludes by exploring WPT as a viable means of recharging EV batteries in an effective and dependable manner. WPT is a desirable option for EV consumers due to its benefits, which include safety, low maintenance, comfort, automated operation, and dependability. The decrease in PTE in the WPT system with an increase in the spacing between the coils is one of the main issues this review addresses. The publication delves deeply into a number of PTE-enhancing approaches, with a focus on research related to WPT technology. It analyzes on various design elements, including compensation strategies, converter topologies, coil designs, and impedance matching, which affect raising system efficiency as a whole. Critically, the study highlights and analyzes existing gaps in WPT technology, providing information about the potential future growth of the static, quasi-dynamic, and dynamic charging methods fields. Also, information provided in this paper useful to get the roadmap for the creation of more dependable and efficient WPT systems, which would ultimately help the EV industry to continue expanding.

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