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Analytical Analysis of Dynamic Wireless Power Transfer System Controllers for Electric Vehicles: A Review

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Abstract: The increase in the Electric Vehicle (EV) market is driven by the desire for more efficient and reliable approaches in charging EV batteries. Among various charging methodologies for EVs, Dynamic Wireless Power Transfer (DWPT) has recently been considered as a promising solution to alleviate the range anxiety and long-charging-duration issue of EVs on highways. However, modeling, controlling, and analyzing the DWPT system are highly challenging because the system dynamics in underlying power system and transportation system have to be jointly considered that makes the problem highly complicated. Thence, the role of advanced control systems becomes increasingly vital in optimizing power transfer efficiency, ensuring system stability, and enhancing user safety. This review systematically categorizes and examines various control strategies employed in DWPT systems, including frequency, phase, amplitude, and hybrid control methods. It delves into the mathematical models and analytical techniques that are used to evaluate these controllers, offering a comparative analysis of their performance metrics such as efficiency, power transfer capability, and robustness. The review also addresses the technical challenges faced with the practical implementation of these systems and identifies current research gaps and future recommendations. By synthesizing the latest advancements and providing critical insights, this review aims to guide future research and development efforts in the field of DWPT systems for EVs.

Keywords: Analytical modeling; Charging and discharging batteries; Control; Dynamic wireless power transfer; Electric vehicles; Review.

1. INTRODUCTION

The current worldwide move towards Electric Vehicles (EVs) is basically motivated by three factors: a decrease in pollution emissions from old-style fuel-powered cars, economically lower maintenance cost, and cleaner energy replacements [1 - 5]. However, despite the benefits mentioned, there are two limiting aspects that delayed the wide EV adoption: the process of charging and the range of driving distance [6 - 8]. Vehicle electrification technologies over the last few years have been performed on the basis that they use generated electricity from renewable energy sources instead of fossil fuels [9 - 12]. However, electricity infrastructures face a significant technological challenge from EVs, since their passive elements constitute a new kind of cargo. Therefore, a large number of EVs can appreciably burden the grid and adversely affect its smooth operation [13]. The primary EV types include Fuel-cell Electric Vehicles, Hybrid electric vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Extended-Range Electric Vehicles (ER-EVs), and Battery Electric Vehicles (BEVs) [14 - 16]. Additionally, concerning EV charging technologies, three common well-known approaches are: static charging involves the vehicle battery charging on a stationary position over the charger [17], dynamic wireless power transfer (DWPT) enables an EV charging while driving [18 - 21], and quasi-dynamic wireless charging [22, 23]. The most important unit of EVs is the battery storage system, associating different types of batteries [24]. Even still, energy storage is the main EVs drawback, which makes EVs traveling over long-distance with a limited amount of electricity unfeasible [25 - 28]. Consequently, for solving the range anxiety, adopting DWPT systems is the utmost talented solution. Correspondingly, DWPT mitigates charging problems of EVs like ongoing distribution of power, current-controlled inverters, and characteristics of Electromotive Force (EMF) as well as decreases further EVs non-technical difficulties including the cost, size, and battery weight [29]. More to the point, other EV components such as converters are used for battery charging, intelligent controllers, EV process of charging, power, and battery energy management concepts [30, 31].

Nowadays, the DWPT charging system is an attractive area of research. Researchers mostly concentrate on improving the efficiency and design of high-power charging systems [32 - 36]. Controllers play an important role in optimizing DWPT systems for EV charging, guaranteeing reliable and efficient transfer of energy [38]. Power transmission parameters such as coil alignment and power levels are dynamically adjusted and optimized by DWPT controllers, which maximize charging efficiency while minimizing electromagnetic interference and energy wastage. Furthermore, efficient controller systems enable faultless integration with EVs, facilitating real-time data exchange and control based on bidirectional communication. By intelligently managing power flow and system operations, controllers improve the overall performance and reliability of DWPT systems by accelerating the adoption of EVs and promoting environmentally friendly transportation solutions [37]. Overall, the primary focus of researchers in DWPT is to develop robust, efficient, and safe wireless charging solutions that meet the growing demand for electric vehicle charging while addressing technical, economic, and environmental challenges.

The motivation for reviewing the analytical analysis of DWPT system controllers lies in the critical need to comprehensively understand and evaluate the current state of control technologies in this rapidly evolving field. DWPT systems represent a cutting-edge approach to EV charging, offering flexibility and convenience. However, the efficiency and effectiveness of these systems mainly depend on the capabilities of controllers in managing power transfer dynamically. By conducting a review of the analytical analysis of DWPT system controllers, researchers and practitioners can gain insights into the latest advancements, challenges, and best practices in controller design and optimization. This knowledge can inform the development of more robust and efficient controllers, ultimately enhancing the performance and reliability of DWPT systems and accelerating the transition toward sustainable transportation solutions.

The paper is structured as follows: Section 1 presents a brief introduction to DWPT in EVs, and in Section 2 background on DWPT systems is presented. In Section 3, the components and operation of DWPT systems are illustrated, and in Section 4 controller techniques of DWPT are stated and analyzed. Section 5 presents the analytical modeling of DWPT controllers, and gaps and perspectives are identified in Section 6. Finally, the conclusion is drawn in Section 7.

2. BACKGROUND ON DYNAMIC WIRELESS POWER TRANSFER SYSTEMS

The concept of charging EVs wirelessly appeared over a century old, as the magnetic induction idea returned to the original work of physicist Michael Faraday at the beginning of the 19th century. Most distinctly, Nikola Tesla (1856–1943) promoted wireless power transmission via electrostatic induction from an induction coil with high tension [38]. After a century, Inductive Power Transfer (IPT) was industrialized in automated factories as an appropriate step for material treatment as well as for EV charging at higher power levels [39]. The mobile state of vehicles charging by using DWPT was realized by Bolger in 1978 [40]. Yet, it was not that important until recent decades were made in evolving well-organized and harmless Wireless Power Transfer (WPT) systems. Nowadays, the foremost four technologies approaches for WPT charging are capacitive WPT [24, 41 - 43], magnetic gear WPT [44, 45], inductive power transfer IPT [47 - 50], and resonant IPT [51 - 54]. The capacitive WPT involves using a capacitor as a device for transferring power, the method is mostly included in low-power applications like a mobile phone and is practical for small gaps [44, 54, 55]. The magnetic gear WPT is a technique that uses permanent magnet positioned alignment and it is significantly inspiring for DWPT. In the inductive WPT technique, shown in Figure 1, the inductive coil is used for power transferring. It is not a complex method, and it has the advantages of flexibility in design, more safety, and further transmission distance [56]. Finally, the resonant inductive WPT approach offers more efficiency and design simplicity of power transfer than other approaches. It employs an inductive coil and a capacitor which is known as a resonant circuit [57]. The above-stated technology approaches allow WPT for important applications such as smartphones [58, 59], electric vehicles [60 - 62], robots, and biomedical implants [63].

3. COMPONENTS AND OPERATION OF DWPT SYSTEM

The concept of DWPT constrains the magnetic coupling between the ground coil known as the primary side coil which is fixed in the road and the secondary side coil installed in the vehicle frame [64, 65]. A representative of DWPT system structure for EV is shown in Figure 2 [66]. One of the hotspot research topics in DWPT is transmitter rail designs [67, 68]. Mainly, there are two kinds of rail designs: long transmitter rail that is uncomplicated and supplies steady power flow for a particular distance. The other type is multiple segmented transmitters rail, each short-track transmitter can be switched ON/OFF according to the EV position [69, 70]. Both types are shown in Figure 3. The first type has the disadvantages of lower Power Transfer Efficiency (PTE) and higher power losses [71- 74].

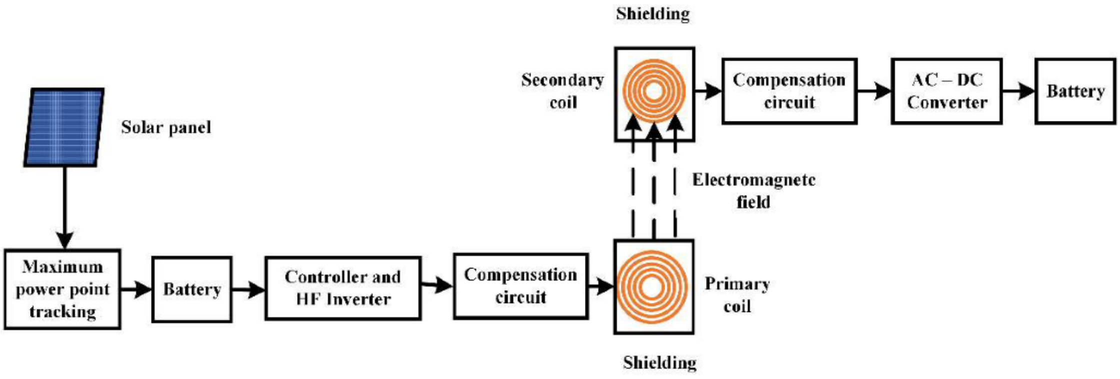


Figure 1. IPT system block diagram.

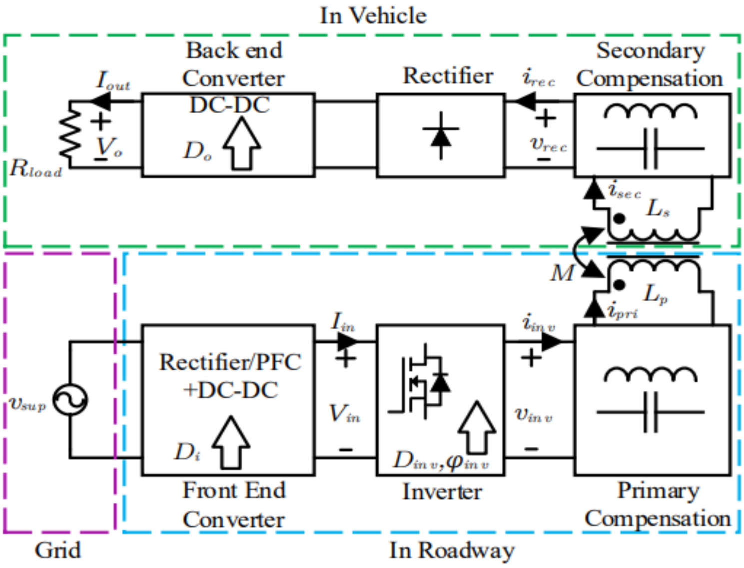
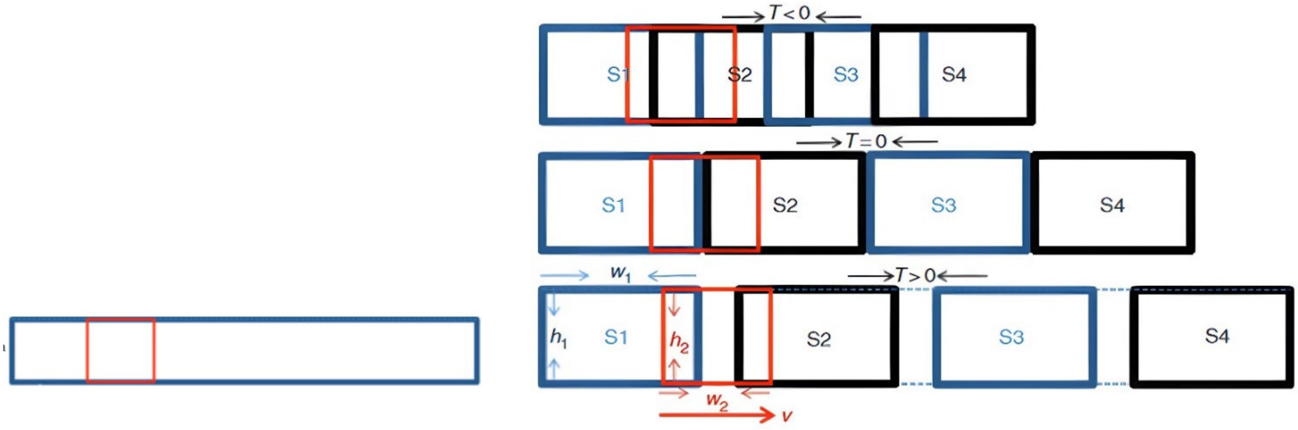


Figure 2. DWPT system stages block diagram.



(a) (b)

Figure 3. Rail design types (a) long transmitter rail and (b) multiple segmented transmitters' rail designs using same receiver (red coil).

The working mechanism of DWPT initially starts with converting the Alternating Current (AC) of the grid to a Direct Current (DC) by an AC-DC rectifier. Then the gained DC power is inverted to high-frequency AC power to feed the transmitter coil via a compensation circuit. After the AC-DC rectifier stage, the high-frequency current in the transmitter coil produces an alternate magnetic field, which induces an AC voltage at the receiver. The amount of voltage induced depends on the Mutual Inductance (*M*) between the two coils, which is always varying in DWPT since the vehicle is in motion and it plays an important role in determining PTE. The mutual inductance *M* is given by Equation (1).

$$M = K\sqrt{L_1 L_2} \tag{1}$$

where *K* represents the coupling coefficient which describes how well the two coils are magnetically coupled, L_1 is the transmitter coil self-inductance and L_2 is the the receiver coil self-inductance.

In the next step of the DWPT working mechanism, the transferred power is improved dramatically via resonating with the secondary side compensation circuit. The gained transferred AC power is rectified and transferred to the DC-DC converter for EV battery charging. The main duty of compensation circuit in the primary side reduces the reactive power of the power supply by neglecting the transmitter coil reactive component [75]. That is to say, it decreases the reactive power at the resonance frequency near 85 kHz which is established by the standards [76]. In addition, the compensation circuit provides a soft switching technique used in power electronics to minimize switching losses and reduce stress on inverter components during the transitions between the ON and OFF states of the switching devices in the road side power converter. Likely, soft switching is employed in the vehicle side enhances the ability of the system power transfer through eliminating the inductance of the receiver circuit. Definitely, the leakage inductances in both sides lead to high positive reactive powers (power required by inductive loads to maintain their magnetic fields), and unwanted powers are compensated by capacitors to achieve efficient and capable improved power transfer [77].

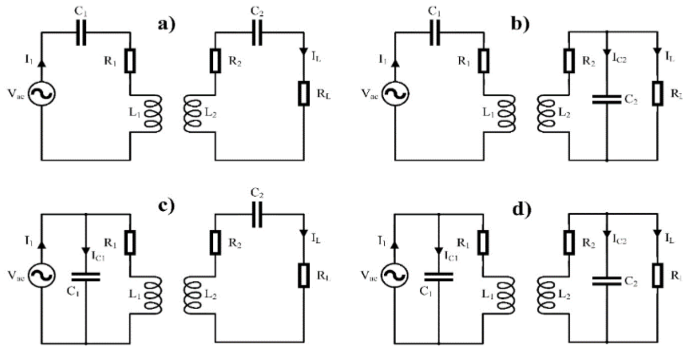


Figure 4. Resonant compensation topologies for primary and secondary resonant circuits (a) SS, (b) SP, (c) PS, and (d) PP.

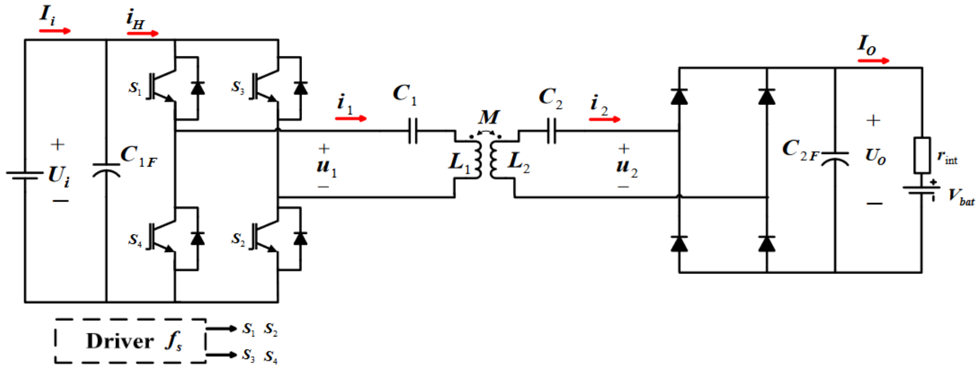


Figure 5. Schematic circuit of IPT system with SS compensation network.

Basically, as shown in Figure 4, the four resonant topologies of resonant inductive WPT systems, the most efficient WPT technologies are: Series-Series (SS), Series-Parallel (SP), Parallel–Series (PS), and Parallel–Parallel (PP) [78 - 80]. Several optimizing approaches for theis technologies were investigated in [81], [82] and [83]. Furthermore, additional compensation topologies might be used for improving the performance of WPT system while they require extra components such as S–LCC, LCC–S, LCCL-S, Series hybrid, LCCL-P and LCC [84 - 89]. The most applicable and high performance topology is SS as shown in Figure 5. An example of IPT system with SS compensation circuit is given in [90].

Recently, several scholars investigated the feasibility of employing the DWPT strategy for powering EVs and verified that it is more economical and environmentally friendly [91 - 95]. Overall, the DWPT system's economic feasibility depends on the coverage of the road, penetration rate of EV, power level, and size of the battery [96]. Besides, several standards have been established for the effective and to secure the use of WPT systems as stated in [91]. Consequently, there is excessive potential in the DWPT real-life applications as it can easily be integrated into many electrical implementations such as light cars, buses, rail, and transport vehicles [97]. Worth mentioning, the growth of electrification considering renewable energy sources has commenced and its ending goal is EVs fully interconnected to Smart Electrical Grids (SEGs). Additionally, technological advancements like 5G wireless communication can increase the use of EVs [98].

4. CONTROLLER TECHNIQUES OF DWPT SYSTEMS

The techniques of enhancing efficiency in power transmission and safety in the control perspective of DWPT systems can be categorized into four classes: frequency control, phase control, amplitude control, and hybrid control. Misalignment, variations in load, and environmental ones are some specific problems to which each class addresses the significant use of DWPT technologies in EVs.

Frequency management is important for the appropriate coordination of the transmitter and receiver coils so as to achieve effective power transfer. The efficient design of inductive power links could be attained with an appropriate selection of working frequencies [99]. This is crucial because the performance of WPT systems is highly reliant on the coils operating at certain resonant frequencies. To support, frequency shifting is required in order to maintain zero-voltage-switching (ZVS) which enhances the performance in terms of effectiveness at higher output power levels of the system as explained in [100, 101]. In addition to this, the design and types of magnetic couplers also determine the frequency control strategies in DWPT systems [102].

Phase-control techniques are enabled by the modification in the phase angle of the power source for better energy transfer, especially in misaligned coils. This approach has also been identified in works that investigated electronic means for tuning misaligned coils to support power efficiency mitigation due to negative effects on misalignment [103]. A frequency has to be maintained to ensure that transmitter and receiver coils are synchronized to work with maximum efficiency. It was concluded that the selection of frequency boosts the effective approach in power transmission systems as the resonance frequency of the coil plays a major role in WPT [99]. For example, the need of the frequency management in achieving ZVS conditions to increase efficiency in high-power applications is highlighted in [101]. Also, the structure and specifications of couplers can influence the regulation techniques used towards frequency in DWPT systems [102].

In research into the optimization of energy transfer, adjusting the phase angles of coils to increase power efficiency in situations when they are not aligned correctly has been identified as an worthy investigation approach [103]. Furthermore, combining phase control with techniques can lead to solutions which take into consideration the variability of both vehicle motion and environmental conditions as suggested by [104]. Amplitude adjustment, on the other hand, which involves the adjustment of input current or voltage to the transmitter coil, for responses to dynamic load conditions, is a method in cases with frequent changes of loads to maintain a consistent efficiency of power transfer [105]. Adaptive control strategies that are self-regulatory and sensitive to these perturbations have proven to improve the maximum efficiency of the WPT systems [106].

The weakened control strategy uses those aspects of frequency, phase, and amplitude control that make it stronger than any of its constituents alone. For instance, when both resonance and alignment are of high importance in scenarios such as that involving high-speed vehicle motion, then frequency and phase control integration can be of great help [107]. This multidimensional approach not only increases the power transfer efficiency but also the robustness of the system to operating conditions and external perturbations. Worth mentioning that the designed controllers for DWPT are applied either on the primary side or secondary side of the system and in some cases, control strategies are implemented for the dual side. Table 1 includes a summary of the DWPT control techniques in terms of controlled variables, control techniques and side where the controllers are applied.

4.1 Frequency Control Techniques

A predominant practice is frequency sweeping, which is the process implies scanning of frequency intervals to determine the effective operating frequency with the maximum power output. This method is beneficial in cases where the condition of the load is not static. Accordingly, a scheme of frequency control based on the splitting characteristics has been developed in order to sustain the steady value of transmission power, such a scheme can solve problems related to the misalignment and load variability [108]. Additionally, it can be deduced that an optimal configuration for multi-receiver systems can reduce the cross-coupling and frequency splitting effects, thus improving the power transfer efficiency of the system [109].

However, as beneficial as it is, the technique of frequency sweeping also causes considerable detuning in the system as a result of changes in the resonant circuit parameters and load conditions that may cause large changes in the power and the coil currents, which is detrimental for safety reasons. To counteract these problems, the authors in [110] suggested a power flow control combining an active impedance tuning subject to a parameter estimation algorithm. This made the looser systems more robust. Also, an adjustable WPT system that uses an incremental algorithm-based frequency examination technique is able to determine the Global Maximum Power (GMP) transfer frequency and maintains self-consistent stability even in multi splitting frequency scenarios [111].

Table 1. DWPT control techniques summary.

Controlled Variable	Control Technique	Reference	Control Side		
			Primary	Secondary	Dual
Frequency	Frequency-Sweeping	[108],[110],[111]	✓		
		[109]			✓
	Variable frequency control	[115],[116]	✓		
		[114]			✓
	Phase-Locked Loop (PLL)	[117],[118]	✓		
	Maximum Power Point Tracking (MPPT)	[120]	✓		
		[119]		✓	
Phase	Zero Voltage Switching (ZVS)	[123-128]	✓		
	Phase Shift Modulation (PSM)	[100],[129],[132],[133]	✓		
		[130]		✓	
		[131]			✓
Amplitude	Phase Width Modulation (PWM)	[134-137]	✓		
	Output voltage regulation	[138],[143],[150]	✓		
		[139-142]		✓	
	Load Management	[144],[145],[149],[151]		✓	
Hybrid	Constant Voltage (CV) and Constant Current (CC)	[155],[156]	✓		
		[154]	✓		
	Output Voltage Regulation and ZVS Operation	[159]	✓		
	Variable Frequency & Phase Shift Modulation (VFPSM)	[161]	✓		
		[165]			✓
	Zero Voltage Switching (ZVS)and Zero Current Switching (ZCS)	[162]	✓		

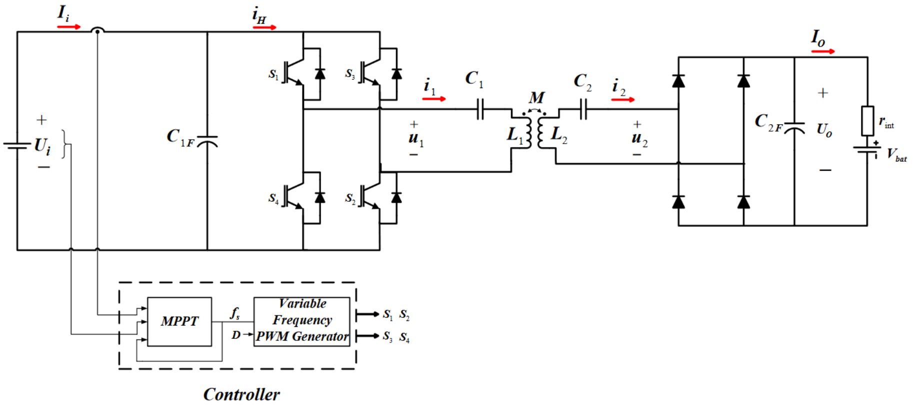


Figure 6. Closed loop control scheme of frequency regulation based MPPT algorithm For IPT system.

Choosing operating frequency is an important parameter that will help and target energy efficiency and voltage controllability for varying load situations. A compensating schemed design to guarantee efficiency and voltage control in series-series compensated inductive power systems was identified in [112]. On the other hand, primary side frequency control scheme in dynamic environments aimed at adjusting the poles phase difference relationship in order to reinforce the resonance when the vehicle shifts position was proposed in [113].

Variable frequency control is another critical technique whereby the frequency is varied in relation to the changing load or coupling. For example, a controller for a series-series network with a variable frequency that tracks and maintains optimal frequency invariable no load output voltage has been presented by [114]. In a similar context, a variable frequency control strategies aimed at improving the efficiency of the DWPT output voltage circuitry at constant loads equally have been executed by [115, 116].

Phase-Locked Loop (PLL), which is frequently used for frequency control, strives to drive the phase error between the secondary current and the primary inverter output voltage to zero. A PLL system was developed for maximum efficiency using the Zero Phase Angle (ZPA) operation to reduce the losses [117]. Moreover, other research highlighted the capability of PLL to improve the frequency control through wide-range operation in field-oriented control [118].

Additionally, the adaptation of Maximum Power Point Tracking (MPPT) methods for frequency control has enabled operation at the point of maximum power transfer in resonance. The frequency controller design utilizing MPPT algorithm is shown in Figure 6 [90]. A buck converter with an MPPT algorithm was utilized based on the extraction of duty cycles as functions of coupling coefficients and frequency values by [119]. The MPPT algorithm can automatically calculate the value of the global resonant frequency resulting in energy efficiency enhancement in different conditions [120]. Perturb & Observe (P&O) methods are likewise promising for frequency control based on small frequency perturbation followed by observations of power transfer [121, 122].

4.2 Phase Control Techniques

Phase control techniques in WPT systems include the adjustment of the phase angle between the current and voltage to optimize the power transfer efficiency ensuring that the system is operating at resonant frequency. The first phase control technique is ZVS, which is a common technique used to minimize switching losses and electromagnetic interference (EMI). Due to the commutation of power converters, the power converter helps switch the state of the system when the voltage drops to near-zero. The benefits of ZVS in terms of increasing the efficiency of WPT were discussed in [123].

A family of converters (buck, boost, buck-boost) could be derived from a general ZVS. To identify that, a generalized type analysis on ZVS synchronous DC-DC converters based on the utilization of coupled inductors is performed [124]. Essentially, the WPT inverter needs to be regulated through a phase shift angle control for ZVS conditions [125]. The ZVS power transfer is crucial for high power delivery while developing a WPT system for electric vehicle chargers with dynamic motion [126]. The fuzzy Proportional-Integral (PI) controller was used to keep the resonance, hence facilitating ZVS under a different set of working conditions [127]. In parallel, the frequency tracking control is tackled with PI parameters tuning to keep ZVS proper resonance conditions [128].

Phase Shift Modulation (PSM) is the other significant technique in DWPT systems, which is based on phase difference adjustment between voltage and current to control power transfer and minimize losses. A novel primary-side synchronous phase-shift control method can improve the power transfer efficiency for DWPT systems [129]. Correspondingly, primary side control strategies were considered strategies for the battery-charging regulation in WPT systems with an added objective of charging efficiency [100]. In this regard, secondary side adjustable rectifiers are used for charging control and efficiency enhancement [130], in which constant current and constant voltage charging with double-sided LCC compensation topology was developed, showing that PSM is also adaptive to different modes of charging [131]. In sum, the purpose of researching new PSM strategies is to make up for the challenges associated with misalignment issues in WPT systems. A WPT system efficiency during dynamic loads is a real challenge and one of the proposed techniques to enhance the system efficiency is an input reactive power control strategy [132]. Moreover, there is an application of digital PLL controllers that was introduced, which can be used for keeping the inverter output and the resonant tank synchronized for maximum power transfer [133].

4.3 Amplitude Control Techniques

In the context of DWPT systems, amplitude control techniques play a pivotal role in enhancing the efficiency of power delivery to EVs. These techniques primarily focus on modulating the voltage or current amplitudes to optimize power transfer. One of the most widely utilized methods is Pulse Width Modulation (PWM), which adjusts the duty cycle of switching signals to control voltage levels effectively. For instance, an output current regulator using a PWM inverter was developed, which incorporates a PI control loop to minimize output voltage ripples [134]. Similarly, a dual-loop controller for roadside DWPT systems was proposed to estimate output power based on the coupling coefficient, thereby managing charging power without the need for additional converters [135].

Moreover, advancements in PWM control strategies have been noted, including the combination of PWM with Phase-Shift (PS) control to mitigate conduction losses associated with higher switching frequencies. A compound control strategy that employs PWM and PLL techniques were introduced to achieve wide output voltage regulation while ensuring ZVS [136]. However, while PWM is straightforward to implement, it is often criticized for its lower performance compared to more sophisticated control methods [137].

In addition to PWM, various other amplitude control techniques have been explored. For instance, buck converters are utilized to dynamically adjust output voltage in response to load variations during vehicle motion, thereby maintaining stability in power transfer [138]. Active rectifiers at the receiver side have also been shown to facilitate wide output voltage regulation in single-stage WPT systems, enhancing overall performance [139 - 142]. Notably, Asymmetrical Clamped Mode (ACM) control has been identified as an effective strategy for managing output voltage fluctuations in series-compensated WPT systems [143].

The efficiency and power delivery in DWPT systems are also influenced by load conditions. The load can be managed through receiver-side DC-DC converters, which adapt to changes in load to ensure optimal power transfer [144]. Moreover, the voltage control on the receiver side maximizes efficiency, thus a complex interplay between transmitter voltage regulation and coupling coefficient estimation was suggested [145]. To simplify ground facilities, a control scheme that utilizes vehicle-side information for voltage estimation was proposed to enhance the operational efficiency of DWPT systems [146].

Power pulsations present a significant challenge in the adoption of DWPT systems. To address this, various control strategies have been implemented. For example, PI and fuzzy controllers were utilized to stabilize the output from a DC-DC buck-boost converter and reduce the power pulsations [147]. Furthermore, two novel control approaches that regulate output power amidst varying mutual inductance were introduced [148]. Supplementary, an optimal load ratio control strategy for dual-receiver systems was proposed to enhance power distribution efficiency without the need for mutual inductance detection [149].

Moreover, designs that accommodate wide variations in output voltage and coupling coefficients were explored [150]. Besides, integrating voltage amplitude control with ZVS techniques was investigated to improve dynamic performance across a broader operational range [151, 152]. Current control methods, which adjust current amplitudes to maintain stable energy transfer despite varying distances and misalignments, have also been highlighted as essential for effective DWPT systems [153].

4.4 Hybrid Control Techniques

Hybrid power control techniques in DWPT systems, particularly in EV applications, have emerged as one of the important research areas that attempt to build upon power transfer efficiency and system stability. These hybrid techniques generally adopt more than one control strategy adaptive to various problems given the conditions of speed, alignment, and load demand issues. One notable example is developing a WPT system that allows both CC and CV outputs to be realized [154]. This could be implemented via a hybrid control strategy that switches between a fixed frequency and self-oscillating control strategies in order to maintain a predefined output voltage independent of load resistance and the coupling coefficient, thus enhancing misalignment tolerance.

Similarly, an IPT hybrid system that customized applications in EV charging was proposed [155]. The system has been characterized by high misalignment tolerance with CC and CV output characteristics to enhance the system's reliability while allowing ZVS and ZPA conditions. A hybrid control strategy that compensates for the dynamic cross-coupling effects in the two-load IPT system to provide consistent power distribution among multiple receivers while achieving ZVS for the inverter was introduced by [156]. Other further improvements were found in the vehicle-side hybrid topology that able to realize CC and CV charging at ZVS conditions without necessarily considering any real-time communication between the coils [157]. This is most beneficial in dynamic conditions where the load condition may vary. An additional strategy to achieve CC and CV outputs with a high-efficiency strategy is a hybrid LCC-SP compensation network with adjustable impedance angles [158].

Other combined control strategies included a hybrid control strategy is proposed for LCC-S-compensated WPT systems [159]. The proposed strategy minimizes reactive current in resonant tanks while offering wide output voltage regulation and ZVS operation. In the same way, this concept is iterated in the literature, where soft switching and tight regulation make the performance of the system better, hence the need for efficient charging modes and technologies in smart charging applications [160].

Among the proposed techniques of dynamic performance improvement is a new hybrid control approach of a resonant full-bridge DC-DC power converter for EV charging systems [161]. This approach, termed Variable Frequency & Phase Shift Modulation (VFPSM), facilitates flexible current switching levels and reduces the Root Mean Square (RMS) current of the transformer, hence optimizes the efficiency of the system. Furthermore, a hybrid control strategy that was based on digital direct phase-shift control was further improving the performance of phase-shifted full-bridge LLC converters [162].

However, researchers have identified that the challenges in controller design complexity and control parameter tuning remain an issue [163 - 166]. Such complexities may limit the practical application of hybrid control strategies in real applications. However, continuous research and development in the hybrid control technique continue to show the way for more efficient and reliable WPT systems for EVs. This fact corroborates comprehensive studies.

5. Analytical Modeling of DWPT Controllers

Analytical modeling of DWPT controllers includes the development of mathematical representations and equations that define the behavior and control of DWPT systems in order to optimize power transfer efficiency and ensure system reliability under variable conditions. The crucial elements of analytical modeling involve electromagnetic coupling, resonant circuit behavior, and power electronics.

5.1 Electromagnetic Coupling

In DWPT system, electromagnetic coupling between the transmitter coil (Tx) and receiver coil (Rx) is crucial to its overall performance. The most significant parameter of electromagnetic coupling, mutual inductance, M was proposed with different analytical models to compute it using approximations and Heuman's lambda function in [65, 167]. Additionally, Measurement methods for obtaining M have also been developed highlighting the necessity of precise identification of electromagnetic parameters [168, 169]. Moreover, controllers and algorithms based on M have been developed to improve the efficiency of the system, by tackling issues like misalignment and movement impact on the magnetic field [170, 171]. Particularly, the coupling coefficient (K) which is a function of M, plays an essential element in system efficiency optimization, and research mostly concentrates on the dynamic behavior of K under misalignment conditions while vehicle is moving [172] and [173]. The coil design in terms of shapes (circular or rectangular configurations, etc.) and coil size has been shown to affect the coupling effectiveness [167, 174]. Lateral developments also have investigated anti-misalignment approaches to improve magnetic coupling and sustain high performance under a variety of conditions [175]. The combination of advanced measurement methods and accurate control strategies based on M can ensure the dynamic environment demand of DWPT, enhancing the overall system performance [169 - 171].

5.2 Resonant Circuit Behavior

In DWPT system, the circuit's resonant behavior is important for power delivery optimization. Traditional modeling methods like Steady-State Averaging (SSA) cannot be utilized to find dynamic models because of having limitations in transient analysis. Therefore, alternative techniques such as Generalized State-Space Averaging (GSSA) and Laplace Phasor Transform (LPT) are being investigated instead [176, 177]. These methods simplify the resonant converters analysis, exhibiting oscillatory behavior which is essential for effective power transfer [178, 179]. Recent research has combined GSSA and LPT methods for quick identification of resonant frequency points in magnetically coupled resonant systems [180]. On the other hand, the coil turns optimization to ensure ZVS over various angles of misalignment has also been explored, indicating important enhancements in coupling efficiency. Moreover, novel dynamic modeling techniques have been derived to handle varying air gaps and load conditions, aiming to improve control schemes to keep on the resonance while the vehicle is driving [181].

5.3 Power Electronics

Power electronics contribute significantly to DWPT system performance through the accurate modeling and optimization of the system components like rectifiers, inverters, and DC-DC converters. The inverter on the primary side converts (DC) to alternating current (AC), and the operating frequency of inverters is near their nominal resonant frequency on the primary and secondary sides of the resonant tanks. This operative characteristic has been widely considered, mainly regarding phase shift control, which seriously affects efficiency and reduces the reactive power losses [174, 182]. The DC-DC converters are integrated on both sides or one side of DWPT system for achieving voltage regulation and impedance matching, resulting in performance improvement of the overall system [104].

The active rectifier implementation has been a pivotal point in recent developments due to its significant contribution in improving the stability of output voltage and dynamic response as well [183, 184]. An active rectifier can adapt to load variation, resulting in optimal performance maintenance in various scenarios. Additionally, the coupling coefficient real-time estimation methods have established the great potential for DC-DC converters' performance enhancement on the secondary side [185]. The importance of this real-time adaptability lies in its involvement in increasing the PTE, particularly in systems with speedy-moving receivers.

Furthermore, the combination of controllable components at the DWPT system's primary side and secondary side has been shown to a considerable enhancement under various operating conditions. The key to improved responsiveness to differences in load and environmental conditions lies in the ability to adjust the parameters of these components dynamically, which ensures the system's efficiency and reliability [186]. For instance, the advanced control strategies based on Kalman filtering allow real-time parameter estimation of DC-DC converters, in that way sophisticating better power electronics control and optimization [187]. This degree of facilitation in control mechanisms is vital for emerging the next-generation power electronics and smart grid systems as pointed out by [174].

6. GAPS AND PERSPECTIVES

Although wireless charging technologies are becoming increasingly a popular research area in both academics and industry, reliability, robustness, and efficiency in EVs charging might be further considered to be enhanced. Control of DWPT systems for EVs is a critical part of research that directly impacts the efficiency, reliability, and scalability of such systems. The identified gaps and perspectives in terms of controller design are as follows:

(a) Maintaining high power transfer efficiency of EV charging wirelessly under dynamic conditions (speed, alignment, coil distance) needs advanced resonance tuning controllers and power management strategies to optimize efficiency dynamically.
(b) It was found that EMI can interrupt the DWPT system operation and interfere with nearby electronics or communication systems. Thus, EMI-aware control algorithms to minimize leakage and ensure compliance with safety standards have to be developed.
(c) Simultaneous charging of multiple vehicles on the same DWPT lane requires dynamic power distribution through the design of real-time multi-objective controllers to balance power delivery.
(d) The distance between the primary and secondary coils is affected by road terrain variation that causes variations in the DWPT mutual inductance. This issue has to be investigated theoretically and experimentally.
(e) The stability and robustness of such a system under varying operating conditions, external disturbances, and parameter uncertainties are not guaranteed. Further adaptive and robust control strategies have to be adopted.

7. CONCLUSION

In this review, a comprehensive analysis of various control strategies applied in DWPT systems for EVs has highlighted the impact of the traditional and advanced controllers on enhancing the overall system performances including reliability, power transfer efficiency, and stability. Moreover, the review emphasized the critical role of accurate analytical modeling in addressing challenges and problems through understanding the interaction between the dynamic and complex nature of the DWPT system. Control techniques such as frequency, phase-shift, amplitude, and hybrid control techniques with their strength and limitations have been stated and analyzed in terms of their character in maintaining efficient power transfer under dynamic conditions. Besides the existing advancements in models and controls, several gaps and challenges remained mainly in real-time control areas, system adaptability, and safe deployment. Therefore, future research directions have to concentrate on control methodologies and system integration including more robust and scalable analytical tools that address the evolving demands of modern EV wireless charging systems. This to ensure that DWPT systems meet the growing demand in EV charging efficiency and reliability on highways. This review serves as a groundwork for upcoming research and development efforts, with the aim of advancing the DWPT field and contributing to EVs extensive adoption.

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