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Next-Generation EV Charging: Innovative Capacitive Wireless Power Transfer Through Harmonic Utilization

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Abstract— **This paper presents a novel capacitive wireless power transfer (CWPT) approach for electric vehicle (EV) charging, using Harmonic Utilization (*Harmion*) to enhance efficiency and compactness. Traditional CWPT systems are constrained by limited power transfer efficiency, primarily due to the inherent capacitance limitations of vehicle chassis. This paper introduces an innovative approach leveraging inverter-generated harmonic components to significantly enhance power transfer efficiency. The proposed method not only overcomes traditional limitations but also reduces inductive component requirements, paving the way for more efficient and cost-effective CWPT solutions. The system minimizes inductor size by tuning the LCLC matching network to a specific harmonic component, reducing weight and improving efficiency. Simulations show Harmion reduces inductance requirements by a factor of nine, lowers voltage stress, and ensures safety compliance, making CWPT a viable alternative to inductive charging for fast charging solutions in electrified vehicles of any mode, e.g., vessels.**

Keywords—wireless power transfer, fast charger, electric vehicles, matching network, harmonic utilization

I. INTRODUCTION

The global transition to electric vehicles (EVs) and plug-in electric vehicles (PEVs) is a cornerstone of international efforts to achieve net-zero carbon emissions by mid-century, as exemplified by the UK's 2050 net-zero policy. EVs and PEVs offer a sustainable alternative to internal combustion engine vehicles, significantly reducing greenhouse gas emissions. According to the International Energy Agency, the global EV fleet surpassed 10 million vehicles in 2020, with projections indicating exponential growth in the coming decades [1]. This shift is driven by stringent environmental regulations, battery technology advancements, and EVs' increasing affordability. However, the widespread adoption of EVs faces several challenges, particularly in terms of charging infrastructure, grid integration, and charging times, which are critical to user convenience and the overall feasibility of EVs as a mainstream transportation solution. One of the primary limitations of PEVs is the time required to recharge their batteries. Conventional charging methods, such as Level 1 and Level 2, can take several hours to fully charge an EV. To address this issue, fast chargers have recently been developed, capable of delivering high power levels. For instance, DC fast chargers, which operate at 250 kW+ power levels, can charge an EV battery to 80% in less than 30 minutes. The adoption of fast chargers is hindered by the lack of standardisation across the globe. For example, the Combined Charging System has widely been used in Europe and North America, while the CHAdeMO standard is prevalent in Japan, and Tesla has its proprietary supercharger network.

The physical connection required for wired charging poses several disadvantages, including wear and tear on charging cables and connectors, the risk of electric shock, the inconvenience of manually plugging it, and limited to static charging only. These issues are particularly problematic in the context of autonomous and self-driving vehicles, where human intervention needs to be minimized. Companies are exploring innovative solutions, such as robotic charging arms [2], to automate the charging process. Hence, there is a growing consensus that wireless charging technology will play a pivotal role in the future of EV infrastructure, with some experts predicting that wired chargers will eventually become obsolete. Currently, wireless charging is widely used in low-power applications, such as smartphones and smartwatches. For EVs and vessels, wireless charging is well-suited for autonomous vehicles, as it enables seamless charging without human intervention. This technology has the potential to advance transport solutions, enabling on-the-go or dynamic charging solutions [3]. Dynamic charging has the potential to revolutionize EV technology by reducing the need for large batteries and extending the EVs' range.

There are two types of wireless energy transfer technologies, including inductive and capacitive methods. Inductive charging, which relies on magnetic fields has been the dominant technology in this field. Initially, the power rating of inductive wireless chargers was limited, but advancements in modular coil structures have enabled the development of high-power inductive chargers capable of delivering fast charging speeds [4]. Several EV technology developers and manufacturers have already incorporated inductive charging systems into their vehicles. For example, Wärtsilä group is developing wireless induction charging systems for hybrid-powered coastal ferries [5], and ENRX is pioneering fully automated wireless inductive charging systems for ferries and vessels [6]. One of the most significant challenges of inductive charging is its sensitivity to misalignment between the vehicle and the charging pad. Even minor misalignments can significantly reduce the efficiency of power transfer, making it difficult to operate at the optimum efficiency. Moreover, the presence of electromagnetic interference (EMI) and the requirement for shielding materials increase costs and complexity. On the other hand, capacitive wireless power transfer (CWPT) offers several advantages over inductive methods. It uses electric fields instead of magnetic fields and it is less sensitive to misalignment and does not require the use of heavy and expensive cores. However, it has historically been limited by its low power transfer capabilities, making it unsuitable for high-power applications like EV charging.

This paper proposes a novel approach to address the limitations of CWPT by utilizing the harmonic components of square-wave voltage generated for wireless power transfer. Since power in a coupling capacitor can only be transferred in the form of AC, square-wave inverters are commonly used in CWPT. However, increasing the switching frequency of these inverters to tens of MHz, as required for high-power CWPT, is not feasible even with soft switching techniques like Zero Voltage Switching (ZVS). To overcome this challenge, this paper introduces a method called Harmonic utilization (Harmion), which leverages the harmonic components of the square-wave voltage to increase the output power level. The innovative approach minimises inductor size by tuning the LCLC matching network to a specific harmonic, reducing weight and improving efficiency. Simulations show that Harmion reduces inductance needs by a factor of nine, lowers voltage stress, and ensures safety compliance. One of the key challenges in CWPT is the limited capacitance available in the chassis of EVs, typically restricted to a few hundred PF. This limitation makes it extremely difficult to achieve the high-power levels required for fast charging. However, Harmion can represent a significant breakthrough in CWPT, offering a pathway to overcome its inherent limitations and establish it as a next generation of wireless charging technology. Making CWPT a viable alternative to other fast charging solutions in electrified vehicles of any mode, e.g., ground vehicles, aircraft, as well as maritime vehicles like vessels. This study make proof of the concept of CWPT as a feasible alternative to inductive charging for high-power applications.

II. THE STRUCTURE OF CWPT FOR EV APPLICATIONS

As shown in the Fig.1, the fundamental structure of a CWPT system includes a 50/60 Hz rectifier that converts AC power from the grid into DC voltage, a high-frequency inverter that transforms the DC voltage into high-frequency AC power, a primary compensator on the ground side that ensures optimal power transfer by compensating for reactive power and tuning the system to operate at resonance, a vehicle-side compensator that matches impedance and steps down the voltage to a battery level, and an onboard rectifier that converts the high-frequency AC power back into DC power to charge the EV battery. One of the primary challenges in capacitive wireless charging is the limited capacitance of the coupler, which arises due to the restricted surface area available on the vehicle chassis and the need to maintain a minimum air gap between the ground-based charger and the vehicle. As a result, the power transfer capability of CWPT is constrained. To overcome these limitations and increase the power transfer level, two key strategies are employed.

The first strategy involves increasing the frequency of AC power. Higher frequencies enable more efficient power transfer through the coupling capacitors, and emerging ultra-fast switches based on wide-bandgap semiconductors such as gallium nitride (GaN) facilitate operation at significantly higher frequencies. Additionally, soft switching techniques such as ZVS reduce switching losses and allow for even higher frequency operation. The application of converters operating at frequencies up to 13.5 MHz has been recently reported for enhancing wireless chargers [7].

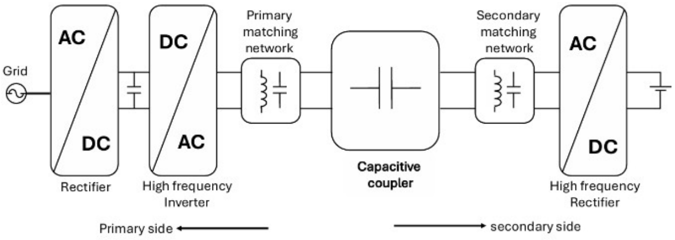


Fig. 1. Fundamental block diagram of the CWPT

The second approach focuses on increasing the voltage level across the coupling capacitors. Since the maximum switching frequency is practically limited, voltage amplification becomes essential. This is achieved using LC passive branches that operate at the resonant frequency to boost the output voltage of the high-frequency inverter. As a result, high-voltage, high-frequency power can be efficiently transferred through the coupling capacitors to the vehicle side.

On the vehicle side, the high-voltage AC power is first stepped down using a matching network, which also boosts the current. A high-frequency rectifier then converts the AC power into DC power to charge the EV battery. Despite the use of high-voltage and high-frequency AC power, the output power level of capacitive chargers remains limited to a few kilowatts according to the latest reports (Table I). This limitation highlights the need for further advancements in system design to enhance power transfer capabilities.

III. CWPT TECHNOLOGY TRENDS

Key publications on CWPT that could potentially be used for EV applications are summarised in Table I. None of these reports are suitable for fast EV charging, as the output power is limited to only a few kW. Unlike inductive chargers, where modular extensions of separate couplers can increase power transfer, capacitive chargers face spatial constraints due to the limited area for coupler, making modular design a significant challenge.

Based on Table I, the majority of reports adopt H-bridge inverter topologies along with diode full-bridge rectifiers, as these configurations enable higher output power compared to half-bridge or Class E converters. However, developing multi-phase CWPT based chargers, such as three-phase configurations, does not necessarily enhance output power. The key limitation is that the available area in the vehicle chassis must be shared between phases, leading to smaller coupling capacitors per phase. This results in reduced wireless power transfer capability, making multi-phase approaches less effective than expected. The dominant compensation topology observed in Table I is LCLC, as it requires smaller inductors, reducing the overall weight of the onboard charger. Additionally, smaller inductors exhibit lower parasitic resistance, which is crucial in ultra-high-frequency converters operating at several MHz. Due to the skin effect, the parasitic resistance of inductors rises significantly at these frequencies, contributing to power losses. Considering the implementation of ZVS strategies to enhance converter efficiency, the major source of power loss in capacitive chargers remains the parasitic resistance of inductive compensation branches. Therefore, minimizing the required value of these inductive components is key to improving efficiency. Any further advancements in CWPT for EV applications should focus on reducing inductive requirements in compensation networks to optimize power transfer performance.

TABLE I. COMPARISON OF THE CWPT APPROACHES

Year	Converter topology	Matching topology	Freq. (MHz)	Air-gap (mm)	Coupler area (m^2)	η(%)	P_{out} (kW)
Ref [8], 2016	H-Bridge Inverter	LCL	1	150	0.91×.61 (Rectangular)	85.87	1.88
Ref [9], 2016	Class E^2	N/A	0.53	0.1	0.1×0.1 (Rectangular)	92	1
Ref [10], 2017	H-Bridge	LC	6.78	120	0.25×0.25 (Rectangular)	90	0.193
Ref [11], 2018	H-Bridge.	LC	13.56	120	0.25×0.25 (Rectangular)	91.3	0.884
Ref [12], 2018	H-Bridge	LC	6.78	120	0.25×0.25 (Rectangular)	89.8	1.2
Ref [13], 2018	H-Bridge.	LCL	1	150	0.61×.61 (Rectangular)	91.6	1.97
Ref [14], 2019	H-Bridge.	LC	6.78	120	0.0118 (Circular)	88.4	1.217
Ref [15], 2019	H-Bridge	LCLC	0.625	150	0.5×0.5 (Rectangular)	80.15	0.1
Ref [16], 2019	3Ph B6 Inverter	LCL	3.4	~1	~0.01 (Shaft-Bearing)	95	0.1
Ref [17], 2020	H-Bridge	LCLC	1	150	0.61×.61 (Rectangular)	93.57	1.5
Ref [18], 2020	H-Bridge	LCLC	1	150	0.61×0.61 (Rectangular)	--	0.3
Ref [19], 2020	H-Bridge	LCL/ L	1	150	0.915×0.915 (Rectangular)	85.5	1.5
Ref [20], 2020	H-Bridge	LC	0.5	~5	0.07 (Circular	88	0.1
Ref [21], 2021	Half-Bridge	LC/L	2	10	0.3×0.3 (Rectangular)	96	0.05
Ref [22], 2022	H-Bridge	LCLC/ LC	~1	1	0.2×0.2 (Rectangular)	84.5	0.110
Ref [23], 2022	H-Bridge	LC/CLC	0.8	150	0.65×0.65 (Rectangular)	90.29	2
Ref [24], 2022	H-Bridge	LCLC	0.5-1.5	6	0.2×0.2 (Rectangular)	83	0.04
Ref [25], 2022	H-Bridge	LCLCLC	6.78	12	0.1×0.1 (Rectangular)	94	0.100
Ref [7], 2022	H-Bridge	LC	13.56	22	~0.1 (Circular)	93	3.75
Ref [26], 2023	H-Bridge	L	1	5	0.3×0.02 (Rectangular, L-shape)	--	0.075
Ref [27], 2024	3-Ph B6 Inverter	LCL	0.5	3	-- (cylindrical)	80	0.8
Ref [28], 2024	H-Bridge	M-M	1	60	0.08 (Rectangular)	87.24	5

IV. HARMONIC UTILIZATION (HARMION) IN LCLC-BASED CAPACITIVE WIRELESS CHARGING SYSTEMS

A. Analysis of the LCLC-based CWPT system

As shown in Table I, high-power chargers commonly use LCLC-based matching networks. These networks are advantageous because they require smaller inductive branches to compensate for the coupling capacitors under resonant operation. Although the concept of Harmion, a new idea proposed in this proof of concept paper, is demonstrated for LCLC-based wireless chargers, it can be extended to other matching networks as well. Under resonant conditions, the use of the LCLC network increases the AC voltage of the high-frequency inverter (V_{in}), significantly enhancing the CWPT through the coupling capacitors (C_s). Fig. 2 shows the equivalent AC circuit of the CWPT. On the vehicle side, the AC voltage is stepped down using a CLCL matching network before rectification. Therefore, V_{out} represents the input voltage of the H-bridge rectifier. To calculate the amount of power transferred through the capacitive coupler in Fig. 2, the superposition theorem can be applied for steady-state analysis.

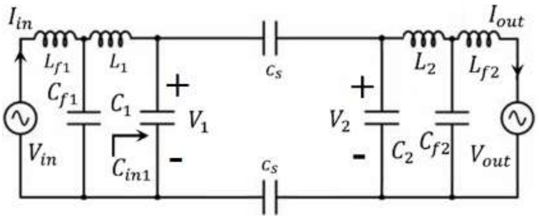


Fig. 2. Equivalent AC circuit of the LCLC-based wireless charger

Assuming the equivalent AC circuit is excited only by V_{in} and that V_{out} is replaced with a short circuit, under resonant operating conditions, L_{f2} and C_{f2} form a parallel resonant circuit, which will behave as an open circuit. Thus, the current through inductor L_2 becomes zero. This leads to the following resonance condition:

$$w = 2\pi f_{sw} = \frac{1}{\sqrt{L_{f2}C_{f2}}} \tag{1}$$

Similarly, L_1 on the primary side forms another parallel resonant circuit with C_{f1} and C_{in1}, where C_{in1} is the equivalent capacitor shown in Fig. 2. Since L_2 and L_{f1} are open circuit in this operating mode, C_{in1} can be calculated as follows. This assumes that $\frac{C_s}{2} \ll C_1$ and C_2.

$$C_{in1} = C_1 + \frac{(\frac{C_s}{2})C_2}{\frac{C_s}{2}+C_2} \approx C_1 + \frac{C_s}{2} \approx C_1 \tag{2}$$

Hence, the switching frequency under resonant mode can be written as follows where C_{in} is the series equivalent of C_{f1} and C_{in1}.

$$w = 2\pi f_{sw} = \frac{1}{\sqrt{L_1 C_{in}}} \tag{3}$$

$$C_{in} = \frac{C_{f1}C_{in1}}{C_{f1}+C_{in1}} \approx \frac{C_{f1}C_1}{C_{f1}+C_1} \tag{4}$$

It should be noted that L_1 and L_{f2} must satisfy equations (1) and (3), based on the selected switching frequency and capacitors, to ensure that the LCLC matching networks operate in resonant mode. In this operating mode, C_{in1}, L_1 and C_{f1} form a parallel resonant circuit, which becomes an open circuit at the resonant frequency, resulting in zero current through L_{f1}. Therefore, V_{in} is directly applied to C_{f1}. Assuming V_1 and V_2 are the voltages across C_1 and C_2 in this mode, using capacitive voltage division:

$$V_1 = \frac{C_{f1}}{C_{in1}} V_{in} \tag{5}$$

Thus:

$$V_1 = \frac{C_{f1}}{C_1} V_{in} \tag{6}$$

$$V_2 = \frac{\frac{C_s}{2}}{C_2+\frac{C_s}{2}} V_1 \approx \frac{\frac{C_s}{2}}{C_2} V_1 \tag{7}$$

Substituting equation (6) into (7):

$$V_2 \approx \frac{\frac{C_s}{2}}{C_2} \frac{C_{f1}}{C_1} V_{in} \tag{8}$$

It should be noted that V_2 is directly applied across C_{f2}, as the current through L_2 is zero, resulting in no voltage drop across L_2. Hence, V_2 is fully transferred to C_{f2}, and the output current I_{out} can be calculated by replacing V_{out} with a short circuit as $\frac{V_2}{\frac{1}{jwC_{f2}}} = jwC_{f2}V_2$. Hence, the magnitude of I_{out} is:

$$I_{out} = wC_{f2}\frac{\frac{C_S}{2}}{C_2}\frac{C_{f1}}{C_1}V_{in} \qquad (9)$$

Assuming $P_{out} = V_{out}I_{out}$, we get:

$$P_{out} = wV_{out}V_{in}\frac{C_S}{2}\frac{C_{f2}(C_{f1})}{C_1C_2} \qquad (10)$$

As the superposition theorem is used to calculate the output power, we may need to analyse the next subcircuit when $V_{in} = 0$, by replacing a short circuit at the input port. However, as there are no power-consuming elements in the circuit under ideal operating conditions, this analysis leads to a similar equation for input power, as no resistive elements are present.

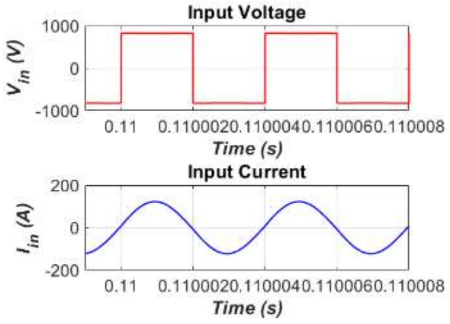
B. Harmion

Based on the above equations, it can be observed that increasing the frequency ($w = 2\pi f_{sw}$) of the AC voltage in the capacitive wireless charger results in increased output power and reduction in required inductive branches: The output power is directly related to the frequency. Thus, increasing the frequency can enhance the maximum power capability of capacitive wireless chargers. Also, all inductive branches are inversely proportional to the square of the frequency. Therefore, increasing the switching frequency significantly reduces the required inductive components (L_1, L_2, L_{f1}, L_{f2}). For instance, if the switching frequency is tripled, the required inductances will decrease by a factor of 9, which is a significant improvement for capacitive wireless chargers. This reduction in inductance improves the efficiency of the wireless charger, addressing one of the main concerns in fast chargers.

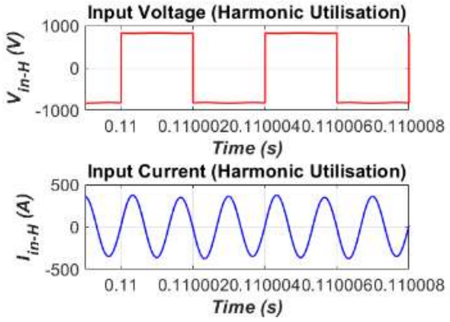
It is important to note that, in high-frequency applications, the skin effect plays a significant role. Decreasing the inductor value reduces the AC internal resistance of the inductive branches, which are responsible for most power losses in capacitive wireless power transfer. However, while increasing the frequency has no direct impact on the required capacitor values in the matching network, harmonic utilization can notably reduce the voltage across the coupling and compensator capacitances. This helps the system meet standard voltage requirements, such as those specified by the IEC standards for wireless chargers.

In wireless power transfer, the switching frequency of converters can be increased up to several MHz using wide-bandgap semiconductors (e.g., GaN switches). However, further increasing the frequency becomes impractical due to switching power loss considerations in the H-bridge circuits. To address this challenge, this study proposes a pioneering method for using harmonic components of the square-wave AC voltage generated by the high-frequency inverter.

By adjusting the LCLC matching network to resonate with a harmonic component (e.g., the third harmonic) of the square-wave voltage, the inverter operates at the main frequency, limiting its switching losses. However, due to the resonance adjustment, only the third harmonic will be transferred through the coupling capacitor. In this design, the inverter operates at the main switching frequency, but the transferred power frequency can be three times higher, which significantly improves the operation of capacitive wireless chargers. This approach allows the output power to potentially increase to meet the demands of fast EV chargers. For instance, if the third harmonic is used, the required inductances (L_1, L_2, L_{f1}, L_{f2}). will decrease by a factor of 9, simplifying the design for high-power applications. Additionally, smaller inductors result in lighter coils, which is



(a)



(b)

Fig. 3. Input voltage/current of the matching network in conventional (a) and harmonic utilization (b)

TABLE II. INITIAL DESIGN PARAMETERS FOR A 60KW CHARGER

Inverter input voltage	Battery voltage	Switching frequency	C_{f1}=C_{f2}	C_1=C_2	C_S
830V	400V	250kHz	*5nF*	*75pF*	*100pF*

TABLE III. REQUIRED INDUCTIVE BRANCHES IN THE MATCHING NETWORKS FOR THE WIRELESS CAPACITIVE CHARGERS

(A) Conventional design

L_{f1}	L_1	L_2	L_{f2}
81uF	*3.94mH*	*3.94mH*	*81uF*

(B) Harmonic utilization

L_{f1-H}	L_{1-H}	L_{2-H}	L_{f2-H}
9uF	*438uH*	*438uH*	*9uF*

TABLE IV. VOLTAGE (RMS) OF THE LC ELEMENTS IN THE MATCHING NETWORKS FOR WIRELESS CAPACITIVE CHARGERS

(A) Conventional design

V_{Lf1}	V_{Cf1}	V_{L1}	V_{C1}	V_{Cs}	V_{C2}	V_{L2}	V_{Cf2}	V_{Lf2}
11 kV	*11.1 kV*	*36 kV*	*36.1 kV*	*13.95 kV*	*29.9 kV*	*28.2 kV*	*14.2 kV*	*14.1 kV*

(B) Harmonic utilization

V_{Lf1-H}	V_{Cf1-H}	V_{L1-H}	V_{C1-H}	V_{Cs-H}	V_{C2-H}	V_{L2-H}	V_{Cf2-H}	V_{Lf2-H}
11 kV	*11.1 kV*	*12 kV*	*14.5 kV*	*9.55 kV*	*26.7 kV*	*27.9 kV*	*4.9 kV*	*4.8 kV*

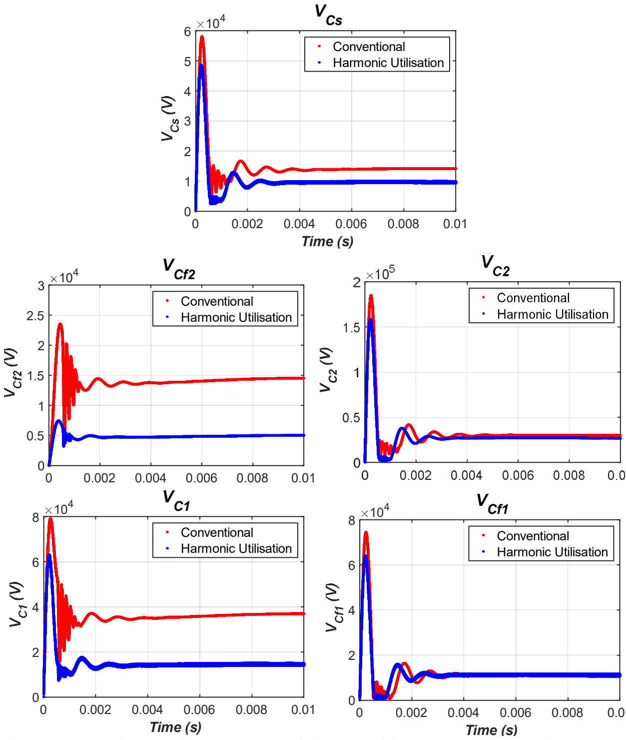


Fig. 4. Transient voltages (rms) of the matching network capacitors

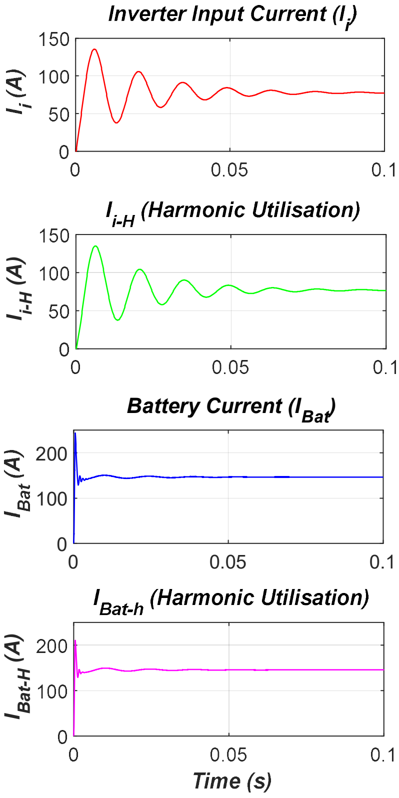


Fig. 5. Inverter input current and load (battery) current during startup.

a key advantage for EV applications, where a lighter charger is desired. Fig. 3 compares the typical voltage and current waveforms of the inverter when the LCLC network is designed to operate at the fundamental harmonic versus when harmonic utilization is applied, with the LCLC network adjusted to resonate at the third harmonic. As mentioned earlier, despite the generation of a square-wave voltage, the current is sinusoidal due to the filtering nature of the LCLC matching networks.

V. SIMULATION RESULTS

A. Comparison of the matching networks for Harmion and conventional CWPT

To compare the requirements of an EV charger, a P_{out}= 60 kW system, illustrated in Fig. 1, is designed. Both chargers—the conventional method and the proposed harmonic utilization technique—use the same initial design parameters, as detailed in Table II. It should be noted that the converter switching frequency is calculated using equation (10), based on the expected output power and the selected capacitors. It is assumed that the duty cycle of the high-frequency inverter is 50%, resulting in an inverter output that is a square-wave AC voltage with no DC component. Since each inductor in the matching networks forms a unique resonant circuit with the selected capacitors in Table II, and based on the design equations outlined in Section III, the required inductor values have been calculated and listed in Table II. In the harmonic utilization method, the effective frequency is 750 kHz, making all inductors nine times smaller than in the conventional method. This significant reduction in the required inductive branches in harmonic utilization leads to a substantial decrease in the volume and weight of the matching networks. Such an achievement serves as a foundation for the widespread adoption of capacitive wireless chargers in next-generation EVs. Notably, if higher harmonic levels are employed, the matching networks can be further miniaturised. However, increasing the harmonic component reduces the effective AC voltage, necessitating the use of higher-current power electronic converters. This highlights the potential application of modular converters in such systems.

B. Steady-state and transient response

Additionally, during steady-state operation, if the third harmonic component is utilized, the effective (RMS) voltage across the L_1, C_1, C_{f2}, and L_{f2} elements decreases by a factor of three. Moreover, the coupling capacitor voltage decreases by 33%. The transient (RMS) voltages of the matching network capacitors during system start-up are illustrated in Fig. 4. To ensure safe operation within the IEC-specified limits for high-voltage elements, the use of electric field shielding in wireless capacitive chargers is mandatory for EV user safety. The lower voltage levels achieved through harmonic utilization represent another significant improvement toward the industrialization of capacitive wireless chargers. In Table IV, rms voltage of the LC elements used in the matching networks are compared for both conventional and harmonic utilization methods.

To validate the output power of the designed wireless charger, the inverter input current, and battery (load) current are shown during system start-up in Fig. 5. During steady-state operation, the battery charging current is approximately 146.5 A, ensuring that the output power exceeds 58.5 kW.

C. Impact of Misalignment on the Proposed CWPT System

In practice, misalignment of the capacitive plates is inevitable due to variations in vehicle parking positions and road conditions. Misalignment can occur in the x, y, or z directions; however, the vertical distance between plates (z-direction) is typically fixed, while misalignment in the x and y directions is more common. Thus, a two-dimensional (x, y) misalignment analysis is performed to examine the impact on system performance.

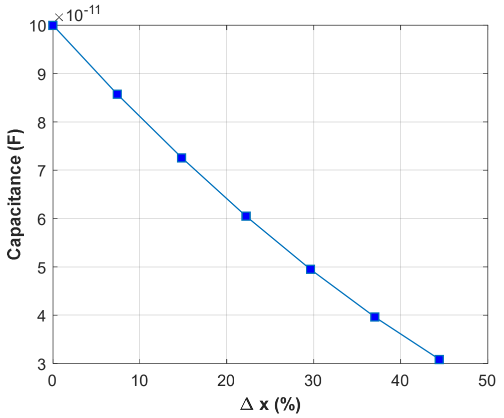


Fig. 6. Coupling capacitance variation as a function of misalignment in the x-direction

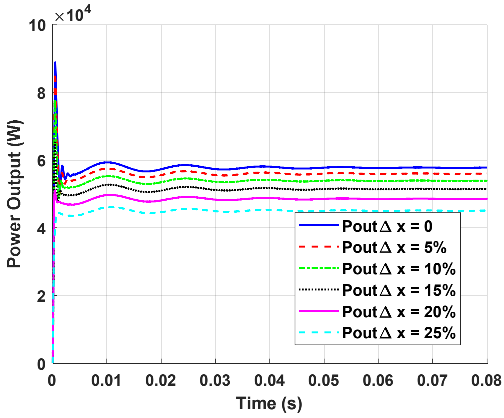


Fig. 7. The impact of misalignment on the system's output power

The coupling capacitance (C_s) in a perfectly aligned condition is given by [29]:

$$C_s = \left[1 + 2.343\left(\frac{d}{l}\right)^{0.891}\right]\frac{\varepsilon l^2}{d} \qquad (11)$$

where l represents the length of the coupling plates, d is the fixed separation between plates, and ε is the permittivity of the medium. To account for misalignment, the dimensions of the coupling plates are adjusted as $l \to (x_0 - \Delta x)$ and $l^2 \to (x_0 - \Delta x)(y_0 - \Delta y)$. Thus, the updated coupling capacitance equation under misalignment is:

$$C_s(\Delta x, \Delta y) = \left[1 + 2.343\left(\frac{d}{x_0 - \Delta x}\right)^{0.891}\right]\frac{\varepsilon (x_0 - \Delta x)(y_0 - \Delta y)}{d} \qquad (12)$$

This equation indicates that as misalignment increases, the effective plate overlap area decreases, leading to a reduction in coupling capacitance. To illustrate this effect, Fig.6 presents the coupling capacitance variation as a function of misalignment in the x-direction, assuming no misalignment in y. It is observed that each percent misalignment results in approximately a 2% drop in the value of the coupling capacitor.

The response of the proposed CWPT system to misalignment can be analysed by varying the coupling capacitance in circuit simulations. Fig.7 presents the impact of varying Δx on the system's output power. It is evident that as misalignment increases, the matching network deviates from its resonant frequency, causing a decrease in transferred power. However, in the harmonic-enhanced operation, the power reduction remains within acceptable limits. For example, at a 20% decrease in coupling capacitance, the transferred power drops by only 10%, highlighting the robustness of the proposed system against misalignment effects.

These results confirm that the harmonic utilization method significantly enhances the misalignment tolerance of CWPT systems, making them more feasible for practical EV charging applications.

VI. CONCLUSION

This paper introduces a next-gen capacitive wireless power transfer (CWPT) method for electric vehicle (EV) charging, employing Harmonic Utilization (Harmion) to enhance efficiency and compactness. By leveraging inverter-generated harmonic components, the approach overcomes traditional chassis capacitance limitations, boosts power transfer, and reduces inductive component requirements. Tuning the LCLC matching network to a specific harmonic minimizes inductor size, cutting weight while improving efficiency. This proof-of-concept study demonstrates a ninefold reduction in inductance needs, lower voltage stress, and safety compliance, establishing CWPT as a practical, cost-effective alternative to inductive charging for fast EV charging across various modes, including vessels and aircraft. Simulation results validate the effectiveness of the proposed harmonic utilization approach in CWPT for EV charging. The numerical comparison between conventional CWPT and harmonic-enhanced CWPT demonstrates a significant reduction in inductive components, with inductor values reduced by a factor of nine. Furthermore, system efficiency is improved, and voltage stress on key components is reduced by up to 33%, contributing to enhanced reliability and compliance with safety regulations. The proposed module successfully delivers over 58.5 kW of power with a battery charging current of approximately 146.5 A, confirming its suitability for high-power EV charging. These results highlight the potential of harmonic utilization in overcoming the inherent limitations of existing capacitive wireless chargers, making them a practical alternative to inductive wireless charging for next-generation EV fast charging infrastructure.

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