

A Low-noise High-frequency Power Supply Based on Linearly-operated MOSFETs for EMF Reduction in WPT Systems

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Abstract—Wireless power transfer (WPT) systems generate leakage magnetic fields due to their operating principle. Therefore, minimizing harmonic electromagnetic fields (EMF) is crucial to comply with standards published by CISPR. A WPT system utilizing a flying-capacitor linear amplifier (FCLA) has been proposed to mitigate radiation noise. However, only low-power experiments had been conducted using the FCLA with the number of MOSFETs limited to two. This paper proposes a high-frequency FCLA with a controller configuration that allows function at high frequencies while minimizing voltage distortion through an open-loop control method that excludes feedback components. Moreover, the gate driver with digital input isolates multi-stage MOSFETs, enabling a high-power output from the FCLA. Experimental results show that the 3.1 kW WPT system employing a 30-series FCLA and a three-level rectifier achieves 91.3% DC-DC efficiency. Moreover, the prototype decreases the third-order harmonic component of radiation noise by 16.0dB compared to the conventional H-bridge-based WPT system with a square-wave output.

Keywords—multi-level linear amplifier, wireless power transfer, electromagnetic field (EMF)

I. INTRODUCTION

Wireless power transfer (WPT) technology is undergoing rapid integration into various sectors, including electric vehicle (EV) charging infrastructure, portable electronic devices, and medical instrumentation. By obviating the necessity for direct physical connections, WPT enhances operational convenience, augmenting safety and system reliability. This evolution signifies a pivotal advancement in the domain of wireless energy dissemination, promising substantial impacts on technological efficiency and user safety. However, several technical challenges must be overcome for its widespread adoption. A significant issue is that WPT systems inherently emit leakage magnetic fields due to the weak magnetic coupling between the transmitting and receiving coils [1–2]. The International Special Committee on Radio Interference (CISPR) has published strict reference levels for

electromagnetic fields (EMF) to prevent this leakage magnetic field from causing malfunctions in nearby wireless communication systems and other electronic devices [3]. Most conventional WPT systems utilize an H-bridge inverter as the power supply due to its high efficiency and simple circuit configuration [4–6]. However, the output voltage from this type of inverter is a square wave, and thus contains numerous harmonic components in addition to the fundamental frequency. These harmonic currents flow into the primary coil, which in turn radiates harmonic leakage magnetic fields. This phenomenon presents a major obstacle to complying with CISPR regulations.

In an effort to mitigate this harmonic radiation noise, various approaches that shape the inverter's output voltage to more closely resemble a sine wave have been investigated. For instance, multi-level converters, which increase the number of voltage steps to smooth the waveform, and pulse-width modulation (PWM) converters, which suppress low-order harmonics by modulating the pulse width, have been proposed [7–9]. While these methods are effective at attenuating the low-order harmonics, their reduction effect is limited. Because they still rely on the switching operation of semiconductor devices, they inherently generate high-frequency noise and waveform distortion caused by factors like dead time, making it difficult to suppress higher-order harmonics.

A promising strategy for fundamentally addressing the issues originating from such switching operations involves adapting a flying-capacitor linear amplifier (FCLA) to WPT systems [10]. Unlike a conventional inverter that uses MOSFETs as on/off switches, an FCLA operates its MOSFETs in their linear region as active devices, similar to a class B amplifier. This allows it to generate an exceptionally smooth voltage that is free of harmonics. Consequently, this approach is expected to suppress harmonic radiation noise dramatically. However, previous research has only demonstrated this effect with a low-power, 2-series FCLA, and a concrete driving methodology for a practical, multi-stage FCLA capable of

handling higher power levels has not yet been established.

Therefore, the primary objective of this paper is to realize a multi-stage FCLA for practical applications. The new contribution of this paper is the establishment of a gate-driving method that precisely coordinates all stages of the multi-stage FCLA to achieve high-fidelity linear operation. Furthermore, we construct a WPT system prototype equipped with the proposed FCLA and the driving technique. Through experimental verification, we demonstrate the significant reduction in third-order harmonic EMF, thereby clearly validating the effectiveness of the proposed method.

II. WPT SYSTEM WITH FLYING-CAPACITOR LINEAR AMPLIFIER

Fig. 1 shows the proposed WPT system with the FCLA. The n -series FCLA consists of n n-MOSFETs, n diodes, an unfolded, resonant capacitors, and coils. The unfolded outputs a sinusoidal voltage by switching the polarity of the full-wave rectified voltage of the FCLA output. The current path of the FCLA depends on the operation modes of each series MOSFET. Thus, an isolated gate driver on each MOSFET must maintain balanced flying capacitor voltages through operation mode selections. A traditional switching power converter uses MOSFETs only in ON or OFF modes. Conversely, FCLA operates in three modes: ON, OFF, and linear, allowing for a continuous output voltage. Fig. 2 shows the drain-source voltage and drain current of the MOSFET in linear operation. Increasing the number of MOSFETs improves the power conversion efficiency of the FCLA, as the drain-source voltage of the MOSFET in linear mode decreases.

In order to reduce harmonic EMF in WPT systems, it is necessary to achieve both primary and secondary side voltage harmonics reduction [8]. Thus, the secondary side of the proposed system is an active bridge rectifier that generates a 3-level voltage waveform to eliminate any order harmonic component [11].

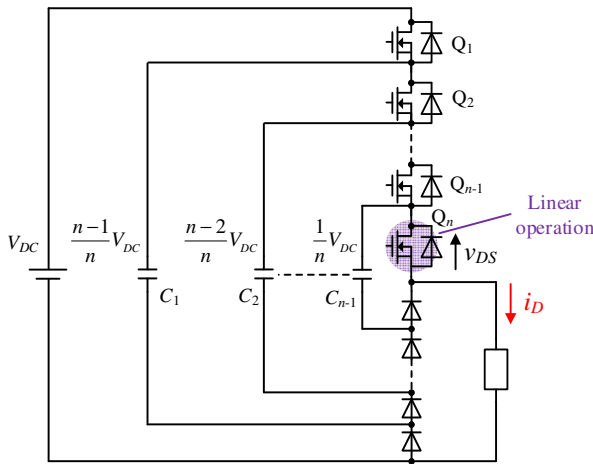


Fig. 2. Drain-source voltage and drain current of linearly operated MOSFET.

III. OPEN-LOOP CONTROLLER

A. Configuration of the controller

To reduce harmonic leakage magnetic fields in WPT systems, achieving both high-quality FCLA output waveforms is essential. Thus, the controller and gate driver have to be capable of driving MOSFETs faster than the output frequency of the FCLA. The proposed configuration of an open-loop controller satisfies both requirements.

Fig. 3 presents the configuration of the proposed controller for high-frequency output. The controller consists of an FPGA (Field-Programmable Gate Array) and isolated gate drivers to control each MOSFET of FCLA independently. Digital isolators insulate the digital signal from the FPGA controller. Digital-to-analog converters (DACs) convert isolated digital signals to analog signals. Finally, amplifier circuits amplify signals from the output of DACs and the source terminal of the MOSFETs. The drain-source voltage of each MOSFET is controlled by a gate driver connected to the drain-gate terminal because each MOSFET of the FCLA acts as a source follower

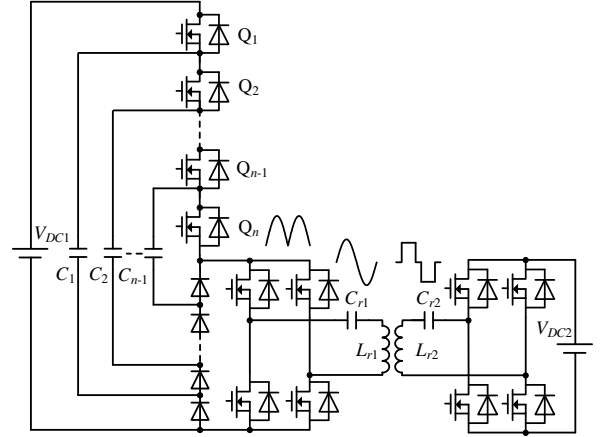
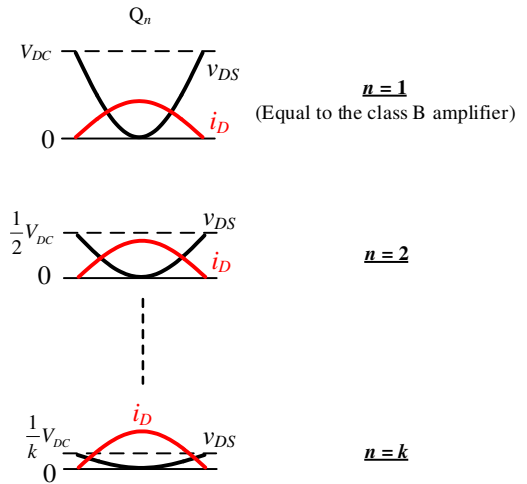


Fig. 1. The proposed wireless power transfer system with a flying-capacitor linear amplifier.



[12]. However, the gate-source voltage is the cause of the output error as shown in (1)

$$v_{DS} = v_{DG} + v_{GS} \quad (1)$$

where v_{DS} is the drain-source voltage, v_{DG} is the drain-gate voltage, and v_{GS} is the gate-source voltage of each MOSFET. Moreover, the gate-source voltage varies nonlinearly because of the threshold voltage and the channel length modulation effect of MOSFETs. Thus, the proposed gate driver has a feedforward of the gate-source voltage for a high-quality

waveform. Each gate driver does the feedforward of the gate-source voltage with reference to its ground. As a result, there is no need for isolation and no delay for compensation.

B. Control method

Fig. 4 shows the FC voltage balance scheme and all operation modes of the FCLA in the case of a two-series FCLA [10]. Three operation modes are selected by comparing phase-shifted carriers with two thresholds that depend on the number of series-connected MOSFETs and the output command of the FCLA. The FCLA has redundant operating modes that output the same voltage with different current paths and charging or

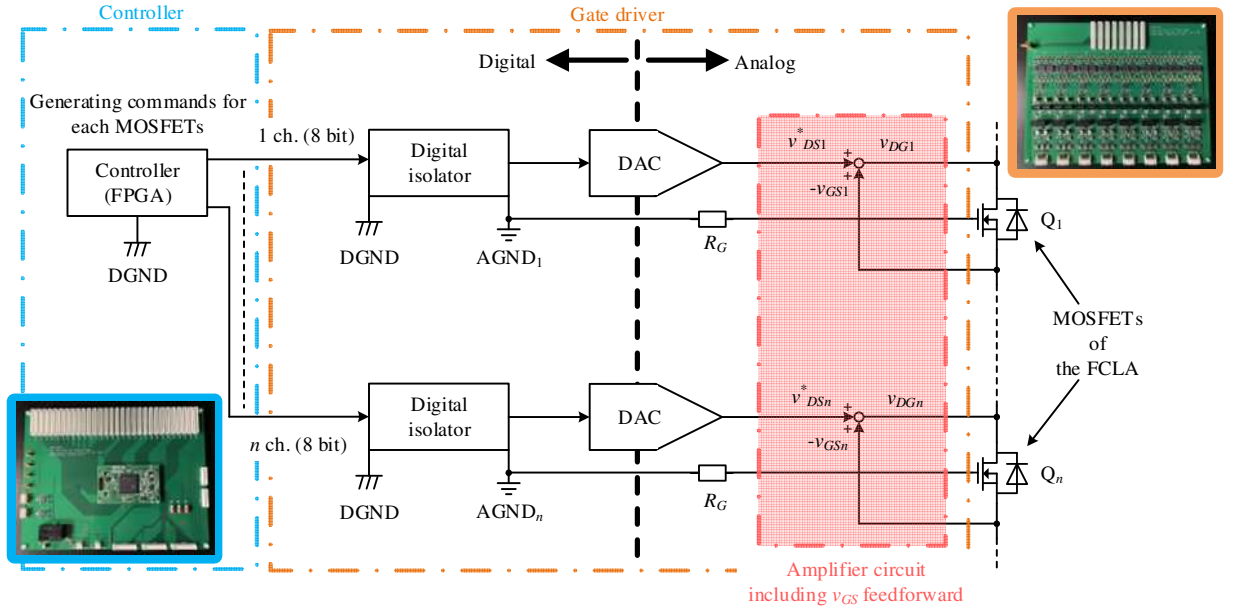


Fig. 3. A configuration of an open-loop controller for driving a high-frequency flying-capacitor linear amplifier.

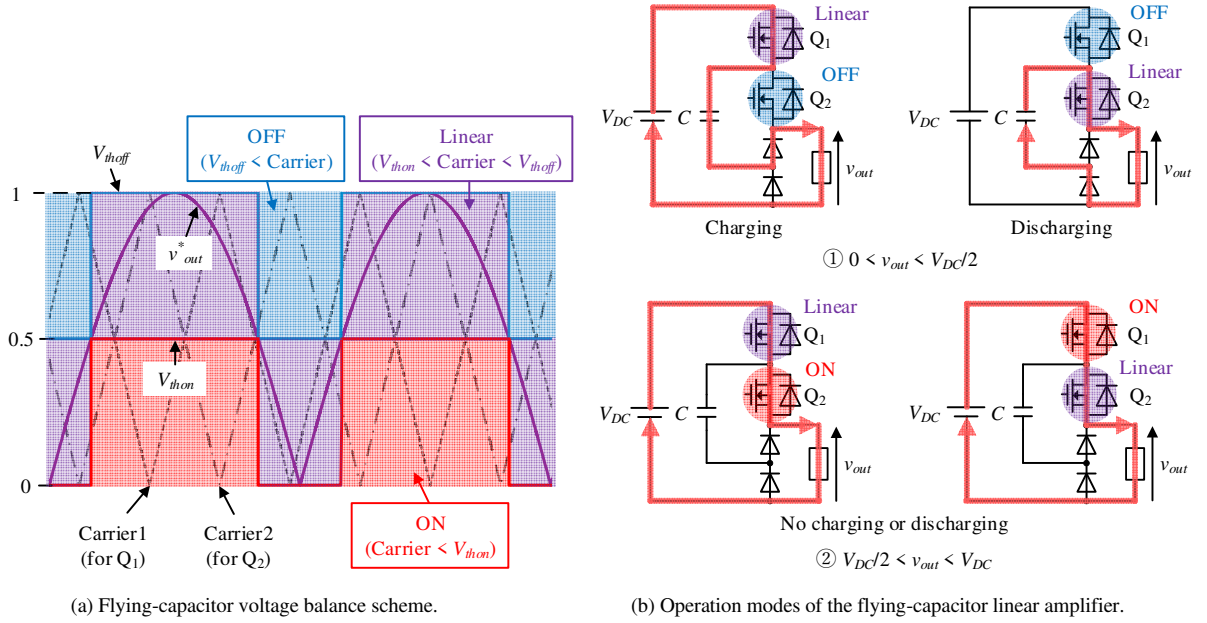


Fig. 4. Operation mode selection of each MOSFET without any feedback.

discharging states of a flying capacitor. Thus, phase-shift carriers with appropriate frequency allow the FCLA to select different current paths within a few cycles. Consequently, the FCLA keeps balanced FC voltages without any feedback components that prevent the high-frequency operation of the gate driver.

IV. EXPERIMENTAL RESULTS

This section experimentally demonstrates the harmonic radiation noise reduction effect achieved by the proposed WPT system, for which a 30-series FCLA prototype has been developed. This multi-stage prototype represents a significant advancement toward practical power levels, enabling the generation of a high-resolution sinusoidal waveform necessary for effective harmonic suppression. The detailed experimental conditions are listed in Table I.

To evaluate the performance and verify the effectiveness of the proposed WPT system with the FCLA in reducing leakage magnetic fields, a comparison was conducted among three types of WPT systems. The section contrasts the WPT system employing the FCLA on the primary side with a conventional system employing a standard voltage-source H-bridge inverter, which inherently generates a rectangular voltage waveform. A critical aspect of this comparative methodology is ensuring that the transmitted power is equal for all systems. This was achieved by applying different DC input voltage levels to the FCLA-based and conventional systems. Equalizing the power transfer ensures that the fundamental component of the coil current is consistent among these setups, allowing for a fair comparison of the harmonic component and the resulting radiated noise. Thereby isolating the impact of the waveform quality from the overall power level.

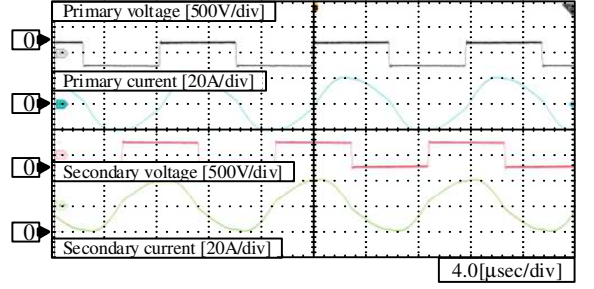
A. Operational Waveforms and Efficiency

Fig. 5 illustrates the operating waveforms of the conventional and proposed WPT systems. Fig. 5 (a) shows the case where both primary and secondary side voltages are square waves. The primary and secondary current is distorted because of voltage harmonics in the square wave voltage. Fig. 5 (b) shows the waveforms where only the primary side is a sinusoidal waveform. The primary current is close to a sinusoidal waveform compared to Fig. 5 (a) owing to the FCLA's sinusoidal output. However, the secondary current is distorted, as shown in Fig. 5(a), because the secondary voltage waveform is the same as that in Fig. 5(a). Fig. 5 (c) represents the case where the primary side voltage is a sinusoidal waveform, and the secondary side voltage is a 3-level waveform. The 0 V output period is adjusted to eliminate third-order harmonics [11]. Both the primary and secondary currents are close to a sinusoidal waveform compared to other systems due to the primary sinusoidal voltage waveform and the secondary 3-level voltage waveform. Thus, it is expected that harmonic components in radiation noise are reduced by this system.

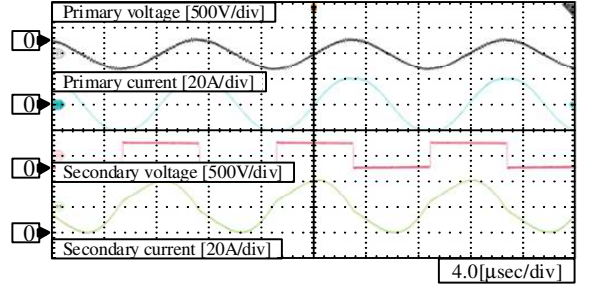
DC input and output power and efficiency of each WPT system are listed in Table II. Efficiency is the DC-DC efficiency of WPT systems. The efficiency of the proposed WPT system (Sin-3 level) is lower than that of the

TABLE I. EXPERIMENTAL CONDITIONS

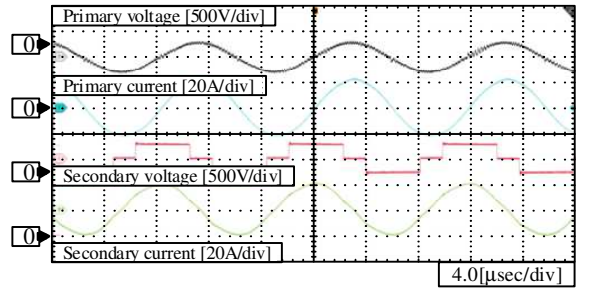
Parameter	Symbol	Value
DC voltage: Sin	V_{DC1}, V_{DC2}	300 V
3-level		272 V
square		236 V
Frequency	f	85 kHz
Primary coil	L_{r1}, L_{r2}	56.2 μ H
Coupling coefficient	k	0.46
Resonant capacitors	C_{r1}, C_{r2}	61.6 nF
Number of MOSFETs	n	30



(a) Conventional WPT system (Square-Square).



(b) WPT system with a flying-capacitor linear amplifier (Sin-Square).



(c) WPT system with a flying-capacitor linear amplifier and H-bridge that has 0 V operation (Sin-3 level).

Fig. 5. Operation mode selection of each MOSFET without any feedback.

TABLE II. POWER AND EFFICIENCY

Waveforms	Input	Output	Efficiency
Square-Square	3.30 kW	3.21 kW	97.2%
Sin-Square	3.33 kW	3.07 kW	92.2%
Sin-3 level	3.43 kW	3.14 kW	91.3%

conventional system (Square-Square) due to the increased number of circuit components. However, the proposed system achieves 91.3% efficiency, which is significantly higher than that of the class B amplifier [12].

B. Harmonic analysis

Fig. 6 presents the harmonic analysis results for the primary and secondary voltages and currents. The harmonic components were analyzed from data measured over 34 cycles of the fundamental frequency.

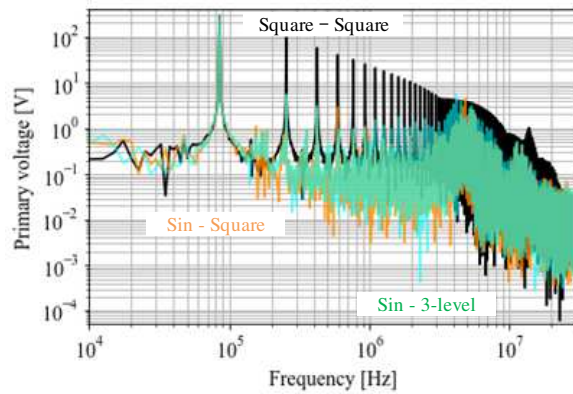
Fig. 6 (a) shows the harmonic analysis result of the primary voltage of each system. FCLA-based WPT systems effectively reduce odd harmonic components compared to the conventional system with a H-bridge inverter due to the sinusoidal voltage output of the FCLA. Fig. 6 (b) shows the harmonic analysis result of the secondary voltage of each system. The system employing the active bridge that generates a 3-level voltage waveform as a rectifier of the secondary side reduces the third-order harmonic component. However, high-order harmonics are increased because the number of switching operations is greater than that of systems using the square wave generating rectifier. Fig. 6 (c) shows the harmonic analysis result of the primary current of each system. FCLA-based

WPT systems reduce odd harmonic components compared to the conventional system with a H-bridge inverter due to the sinusoidal voltage output of the FCLA. However, harmonic reduction effects are different for voltage waveforms on the secondary side. This is because harmonic components of the primary and secondary sides interfere with each other due to magnetic coupling [8]. Thus, the FCLA-based WPT system with a 3-level rectifier remarkably reduces the third-order harmonic component. Fig. 6 (d) shows the harmonic analysis result of the secondary current of each system. The system employing the active bridge that generates a 3-level voltage waveform as a rectifier of the secondary side reduces the third-order harmonic component.

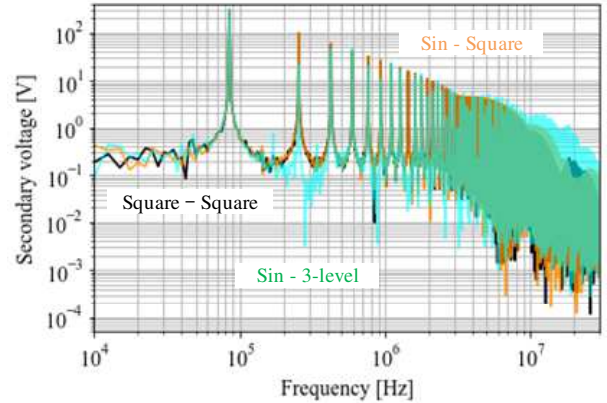
C. Radiation Noise

Fig. 7 shows the measurement results of the leakage magnetic field radiated from the WPT systems. The measurements were conducted using a loop antenna (EM-6992, 6 cm H-field) positioned 1.2 m from the center point between the transmitting and receiving coils.

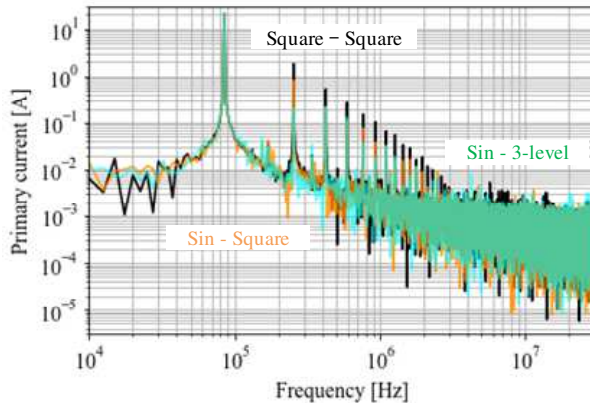
As shown in Fig. 7, the FCLA-based WPT system reduces the odd-harmonic components of the radiation noise compared to the conventional H-bridge-based system. Especially, the



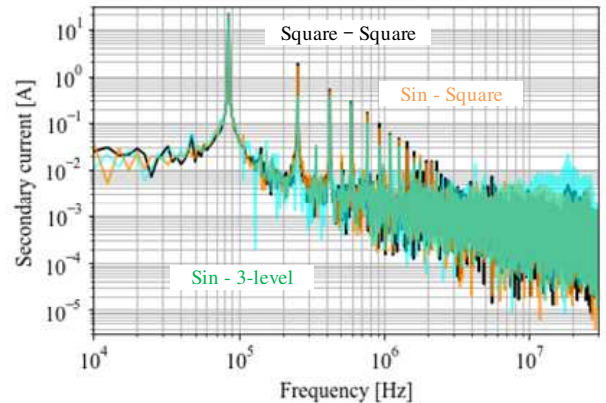
(a) Primary voltage.



(b) Secondary voltage.



(c) Primary current.



(d) Secondary current.

Fig. 6. Harmonic analysis of the voltage and current.

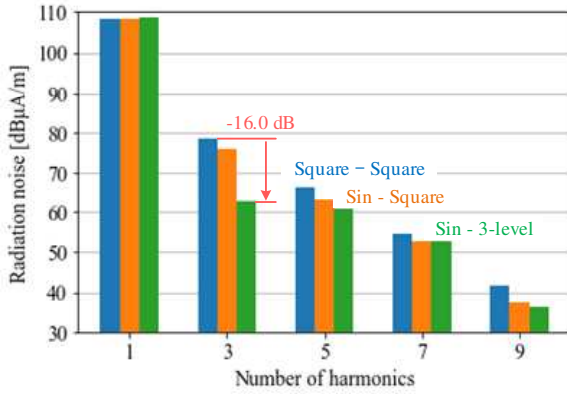


Fig. 7. Radiation noise.

FCLA-based WPT system employing the active bridge that generates a 3-level voltage waveform as a rectifier of the secondary side reduces the third-order harmonic component by 16.0 dB.

V. CONCLUSION

This study proposes and empirically validates a comprehensive methodology to address the critical issue of harmonic radiation noise in high-power wireless power transfer (WPT) systems. To address the inherent harmonic content generated by conventional square-wave inverters, a high-frequency, multi-stage Flying Capacitor Linear Amplifier (FCLA) was developed as a high-fidelity primary-side power source. This research demonstrates a fundamental approach to suppressing harmonic emissions by generating a pure sinusoidal voltage at the source. This work provides a method to comply with stringent electromagnetic compatibility standards, such as those from CISPR.

A key contribution of this work is the development of a novel open-loop controller architecture that enables stable and precise operation of the multi-stage FCLA at high frequencies. Realizing high-fidelity linear operation in a system with numerous series-connected stages presents a significant challenge. The proposed controller successfully overcomes this by incorporating a localized, high-speed feedforward compensation for the gate-source voltage, thereby minimizing waveform distortion without the inherent bandwidth and stability limitations of traditional feedback-based control loops.

The practical viability of this approach was demonstrated through extensive experimental validation on a 3.1 kW WPT system. The construction of a 30-stage FCLA prototype confirmed the scalability of the proposed architecture to practical power and voltage levels. The system, which combines the primary-side FCLA with a secondary-side 3-level active rectifier, achieved a DC-DC efficiency of 91.3%. While this is inherently lower than the conventional H-bridge-based WPT system, it is a remarkably high efficiency for a linear amplifier at this power level and validates the effectiveness of the multi-stage topology in suppressing

conduction losses. Most importantly, the proposed system successfully reduces the critical third-order harmonic component of the radiation noise by 16.0 dB compared to a conventional H-bridge-based system.

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