Low-Harmonic-Distortion and High-Efficiency Class E^2 DC-DC Converter for 6.78 MHz WPT

Shuangke Liu
University of Michigan-Shanghai
Jiao Tong University Joint Institute,
Shanghai Jiao Tong University,
Shanghai, China, 200240
Email: liushuangke@sjtu.edu.cn

Chengbin Ma
University of Michigan-Shanghai
Jiao Tong University Joint Institute,
Shanghai Jiao Tong University,
Shanghai, China, 200240
Email: chbma@sjtu.edu.cn

***Abstract*—The Class E^2 dc-dc converter, composed by soft-switching based Class E power amplifier (PA) and rectifier, is popular for 6.78 MHz wireless power transfer (WPT) for its high efficiency and simple topology. Here, we take a comprehensive analysis on the harmonic voltages and currents on the transmitting and receiving coils in a Class E^2 dc-dc converter. These harmonics can be radiated into the free space through the coils, causing low system efficiency and electromagnetic interference (EMI) issues. And thus, it is expected to eliminate these harmonics. Next, an improved Class E^2 dc-dc converter with low harmonic distortion and high efficiency is proposed. The harmonic distortions on both receiving and transmitting coils are greatly reduced by the employment of the full-wave Class E rectifier and Pi impedance transformation network. The total harmonic distortion (THD) of voltages and currents are less than 57.5% of those of the classical system. In addition to the reduction of harmonic distortion, the proposed converter is able to maintain high efficiencies, over 70%, when the coil coupling changes, by carefully designing the Pi network.**

I. INTRODUCTION

The techniques of 6.78 MHz wireless power transfer (WPT) have been achieving intensive attentions both from academia and industry, due to the high transfer efficiency and compact circuit size [1]–[3]. It is promising to be widely applied to charging to various consumer electronics wirelessly, such as phones, implantable medical devices, electric vehicles, and so on. It is believed that the WPT will provide a safer and more convenient user experience. However, there are still many challenges in real applications, for instance, the high switching losses, harmonic distortions, and sensitivity to the variation of operating conditions.

At the operating frequency of 6.78 MHz, the switching time of MOSFETs and diodes used for power conversion becomes comparable to the switching cycle, resulting in substantial switching loss [4]. Fast switching components have to be applied in the MHz WPT systems and soft-switching techniques should be employed to reduce the switching loss. Class E^2 dc-dc converter is a good candidate for 6.78 MHz WPT system [5], [6]. It is composed by the soft-switching Class E PA and rectifier. The parameters of Class E PA are carefully designed so that the drain voltage and its derivation reach to zero at the end of switch-off period, i.e. zero voltage switching (ZVS) and zero voltage derivation switching (ZVDS) conditions [7], [8]. The Class E rectifier uses only one diode as switch. A capacitor is connected in parallel with the diode so that the voltage across the diode varies with a slow rate at the instants of switching on and off [9]. A very high system efficiency for Class E^2 dc-dc converter, about 84%, has been observed in experiments [4].

Here, intensive research on reducing the harmonic distortions in 6.78 MHz Class E^2 dc-dc converter for WPT is presented in this paper. The harmonic voltages and currents on the transmitting and receiving coils can be radiated into the free space through the coils. They will lead to a reduced system efficiency and may also cause the electromagnetic interference (EMI) issues to other devices nearby. Besides, there are many standards organizations, such as Federal Communications Commission (FCC), International Commission on Non-Ionizing Radiation Protection (ICNIRP), and the Institute of Electrical and Electronics Engineers (IEEE C95.1), regulate the human exposure in the electric, magnetic, and electromagnetic fields [10]–[13]. The customer electronics using WPT circuits have to be certified by these standards. Thus, it is essential to take a comprehensive analysis on the harmonic distortion in the WPT system and eliminate the harmonics as much as possible. In this paper, the source of harmonics are analyzed, and effective methods are proposed to reduce the harmonic distortions by employing a Pi impedance transformation network and full-wave Class E rectifier.

In addition to the reduction of harmonic distortion, high efficiency and robustness against the variation of coil coupling are achieved by careful design of the Pi impedance transformation network. As presented in [14], the Class E^2 dc-dc converter is superior to other system topologies due to the high power transfer efficiency, but it is sensitive to the variation of operating conditions. The system efficiency decreases when the operating conditions deviate from the optimum status [14]. Kinds of adaptive approaches have been developed to deal with the variation of operating conditions, such as frequency tuning, PWM control, tunable capacitors and inductors, and so on [15]–[19]. However, in these tuning and controlling methods, tracking and controlling circuits have to be employed, leading to increased circuit complexity inevitably. As presented in [20], the Class E PA is most sensitive

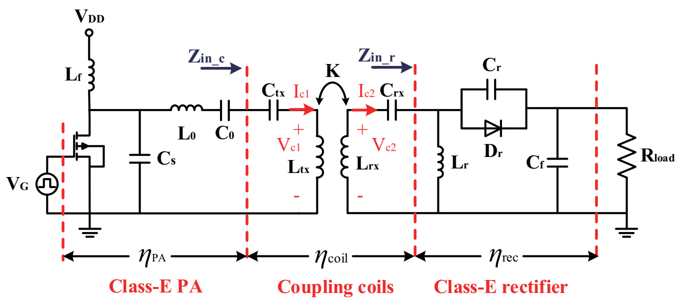

Fig. 1. Configuration of a classical Class E^2 dc-dc converter for 6.78 MHz WPT.

to the variation of operating condition compared to the coils and rectifier. The efficiency of PA decreases substantially for the mismatch of PA's load. Here, we will prove that a fixed Pi impedance transformation network, inserting between the PA and transmitting coil, is sufficient to keep a high system efficiency through the optimization of circuit parameters.

This paper is organized as follows. Section II provides a comprehensive analysis on the harmonic distortions in the classical Class E^2 dc-dc converter. Two equivalent circuits are utilized to distinguish and evaluate the source of harmonic distortions. And then, an improved Class E^2 dc-dc converter employing a Pi impedance transformation network and a full-wave Class E rectifier is presented in Section III. The proposed converter shows great superiority both in harmonic reduction and improved efficiency robustness.

II. Harmonic Distortions in a Classical Class E^2 DC-DC Converter

The configuration of a classical Class E^2 dc-dc converter designed for 6.78 MHz WPT is shown in Fig. 1. It is composed by three parts, a Class E PA, coupling coils, and a half-wave Class E rectifier. The parameters of transmitting and receiving coils are extracted from real circuits. And then, the optimum load of coupling coils is calculated. Next, the half-wave Class E rectifier is designed to provide this optimum load. Finally, the Class E PA is designed according to the input impedance of the transmitting coil and output power. Details of design procedure are presented in [4]. The Advanced Design System (ADS), a high-frequency circuit simulation software, is utilized to simulate circuits. The circuit parameters used in simulations are shown in Table I.

The proposed Class E^2 dc-dc converter is able to achieve very high system efficiency, about 80% with 12.6 W output power, under optimum operating condition. Here, in this paper, we focus on the analysis and elimination of harmonic distortions on the transmitting and receiving coils. Fig. 2 shows the spectrum of V_{c1}, V_{c2}, I_{c1}, and I_{c2}, which are the voltages across the transmitting and receiving coils and the currents through them. The harmonic contents of these voltages and currents are unexpired. They constitute time-variant electric and magnetic fields at harmonic frequencies in the free space, which may induce EMI problems to other devices nearby. Besides, many standards restrict the strength of

TABLE I
Circuit Parameters of the Classical Class E^2 DC-DC Converter.

Class E PA	L_f (10 μH)	RF choke
	C_s (287 pF)	shunt capacitor
	L_0 (1.87 μH)	filter inductor
	C_0 (376 pF)	filter capacitor
Coupling Coils	L_{tx} (1.78 μH)	inductance of transmitting coil
	r_{tx} (0.55 Ω)	equivalent series resistance of L_{tx}
	C_{tx} (310 pF)	compensation capacitor
	L_{rx} (0.83 μH)	inductance of receiving coil
	r_{rx} (0.15 Ω)	equivalent series resistance of L_{rx}
	C_{rx} (800 pF)	compensation capacitor
	k (0.15)	coupling coefficient
Class E Rectifier	L_r (68 μH)	RF choke
	r_{L_r} (0.2 Ω)	equivalent series resistance of L_r
	C_r (1450 pF)	shunt capacitor
	C_f (44 μF)	DC filter capacitor

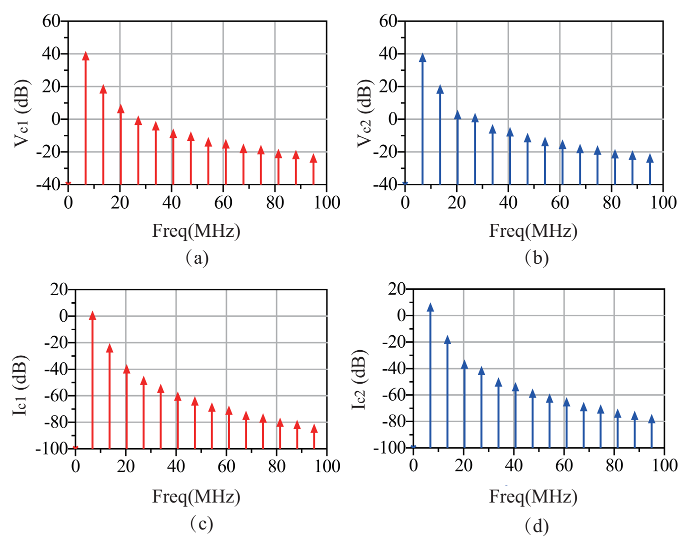

Fig. 2. Spectrum of V_{c1}, V_{c2}, I_{c1}, and I_{c2}. (a) V_{c1}. (b) V_{c2}. (c) I_{c1}. (d) I_{c2}.

electric, magnetic, and electromagnetic fileds in the free space to protect people from excessive exposure. Thus, it is expected to eliminate these harmonic contents as much as possible.

The harmonic contents of voltages and currents of coils mainly come from two aspects: non-ideality of the filter in Class E PA and the switching procedure in the rectifier. The filter used in the Class E PA is a series LC resonant circuit, which are L_0 and C_0, as shown in Fig. 1. The current with operating frequency, i.e. 6.78 MHz, passes through this filter and the others are rejected for high equivalent impedance at harmonic frequencies. The larger L_0, the better filtering performance. However, inductors with very large value are usually undesired, due to the bulky volume and low quality factor. A few harmonic currents pass through the filter and act on the transmitting coil. The voltage across the receiving coil becomes non-sinusoidal due to the switch on and off of the diode, and thus harmonic contents are generated on the receiving coil. The harmonic voltages and currents on

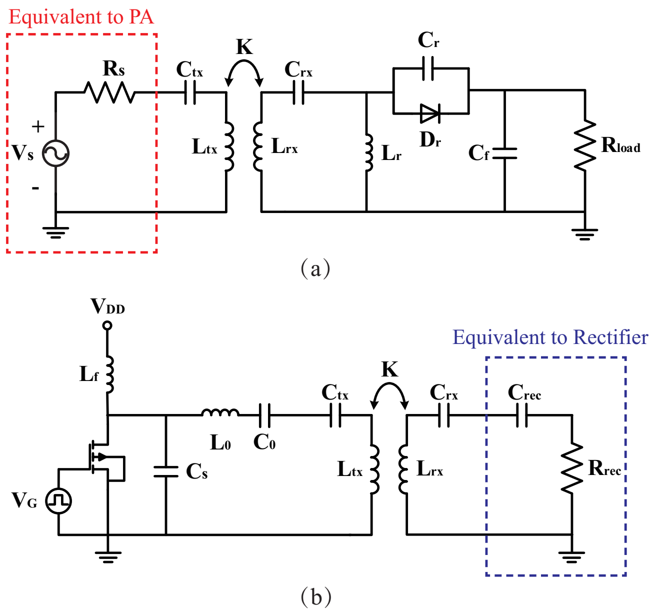

Fig. 3. Two equivalent systems. (a) Sys1. (b) Sys2 .

TABLE II
VOLTAGE AND CURRENT THDS OF TRANSMITTING AND RECEIVING COILS.

	V_{c1}	I_{c1}	V_{c2}	I_{c2}
Original	10.1%	8.2%	11.03%	5.98%
Sys1	0.76%	1.43%	10.79%	5.49%
Sys2	10.58%	5.44%	0.41%	0.82%

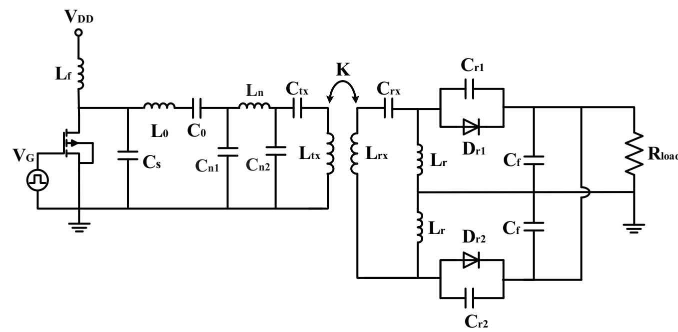

Fig. 4. Configuration of the improved Class E^2 dc-dc converter.

the transmitting coil is able to transform to the receiving coil through coupling, and vice versa. To distinguish the main source of the harmonic voltages and currents on the transmitting and receiving coils, two equivalent systems, Sys1 and Sys2, illustrated in Fig. 3, are simulated.

In Sys1, the Class E PA is replaced by a voltage source and a source impedance. The source impedance is equal to the conjugate of the input impedance of the transmitting coil, i.e. Z_{in_c}. The voltage source provides an I_{c1} equal to that of original system illustrated in Fig. 1. With this setup, the rectifier is the only source of harmonic contents in the whole system. In Sys2, the rectifier is replaced by a resistor and capacitor, the equivalent impedance of which is equal to the input impedance of rectifier at fundamental frequency, i.e. Z_{in_r}. Under this circumstance, all the harmonic distortions come from the PA. With the comparison of Sys1, Sys2, and the original system, we can figure out where the harmonic contents come from and evaluate their contributions. Here, the total harmonic distortion (THD) is used to evaluate the harmonic contents of the WPT system. The definition of voltage and current THDs are depicted in (1). V_n and I_n are the voltage and current at n-th harmonic frequency.

$$\text{THDV} = \frac{\sqrt{\sum\limits_{n=2}^{\infty} V_n^2}}{V_1} \times 100\%, \ \ \text{THDI} = \frac{\sqrt{\sum\limits_{n=2}^{\infty} I_n^2}}{I_1} \times 100\%. \quad (1)$$

The voltage and current THDs of the coils are listed in Table II. It can be concluded that: a) the harmonic voltages and currents are able to transform between the transmitting and receiving coils, while their contribution is small; b) the harmonic voltage and current on the transmitting coil mainly come from the PA; c) the harmonic voltage and current on the receiving coil are generated from the rectifier mostly. Therefore, measures have to be taken on both the PA and rectifier to eliminate the harmonic voltages and currents.

III. Improved Class E^2 DC-DC Converter

Here, we propose an improved Class E^2 dc-dc converter with low harmonic distortions and high efficiency, as illustrated in Fig. 4. A Pi impedance transformation network is inserted between the PA and transmitting coil, and the half-wave Class E rectifier is replaced by the full-wave Class E rectifier.

Detailed design process of full-wave Class E rectifier for WPT system can be found in [21]. The full-wave rectifier is a balance circuit. Thus, the even harmonic distortions can be reduced significantly. Fig. 5 shows the harmonic voltage and current of the receiving coil when the full-wave Class E rectifier is used. It has to be mentioned that the value of shunt capacitor C_r in the full-wave Class E rectifier is increased from 1450 to 2300 pF, in order to keep the same output power to the original system analyzed in Section II. This measure is essential because the parasitics in MOSFET and diode are power depended and their influence on the performance should be eliminated in the comparison. The THD of V_{c2} and I_{c2} are 3.72% and 1.73%, which are much smaller compared to those in the original system.

The harmonic voltage and current on the transmitting coil can be reduced directly by replacing the L_0 with shunt resonant circuits. Fig. 6 presents an improved filter with the second and third harmonic current rejection. L_{H2} and C_{H2} are resonant at the second harmonic frequency, L_{H3} and C_{H3} are resonant at the third harmonic frequency, and the circuit in the dash frame is equivalent to L_0 at the fundamental frequency. Table III shows the voltage and current THDs when

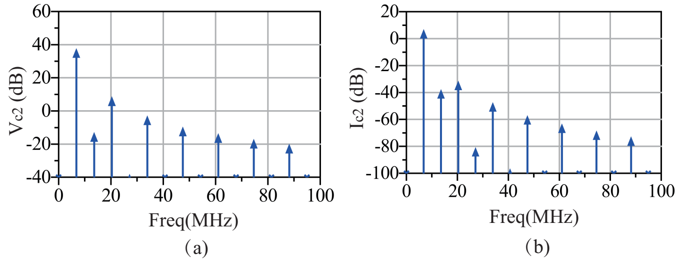

Fig. 5. Spectrum of V_{c2} and I_{c2} for converter with full-wave Class E rectifier. (a) V_{c2}. (b) I_{c2}.

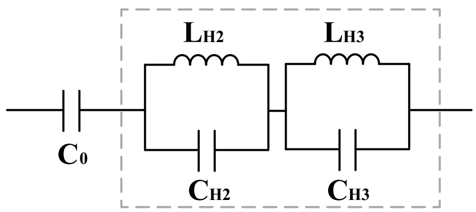

Fig. 6. Configuration of the improved filter in PA with the second and third harmonics rejection.

the shunt resonant circuits and full-wave Class E rectifier are used in the converter. It shows that the harmonic distortions are eliminated efficiently. Instead of this shunt resonant circuit, here in this paper, a Pi impedance transformation inserting between the PA and transmitting coil is proposed. Besides the function of eliminating harmonic distortions, this Pi impedance transformation network is also able to keep the load of PA staying in an expected region when the coupling of coils changes, where the efficiency of PA maintains high.

Fig. 7 illustrates the efficiency contours when the load of PA varies. It can be found that the efficiency decreases monotonously when the load of PA deviates from the optimum load. The blue line in Fig. 7 presents the variation of Z_{in_c} when the coupling coefficient of coils changes from 0.1 to 0.3. Part of this line locates in the low efficiency region, indicating low efficiencies of PA when the coupling changes. Thus, the Pi impedance transformation network can be used to transform all the Z_{in_c} into a high efficiency region. Here, we define the area within the 90% efficiency contour in Fig. 7 is the high efficiency region. Above all, the parameters of the Pi impedance transformation network is optimized to satisfy the following two constrains: a) all the Z_{in_n}, the input impedance of the Pi network, are within the high efficiency region and close to the optimum load of PA as much as possible, i.e. (2) is as small as possible when K varies from 0.1 to 0.3; b)

TABLE III
VOLTAGE AND CURRENT THDS OF TRANSMITTING AND RECEIVING COILS FOR SYSTEMS WITH FULL-WAVE CLASS E RECTIFIER.

	V_{c1}	I_{c1}	V_{c2}	I_{c2}
with shunt LC	6.6%	1.6%	5.95%	1.21%
with Pi network	5.81%	3%	3.72%	1.73%

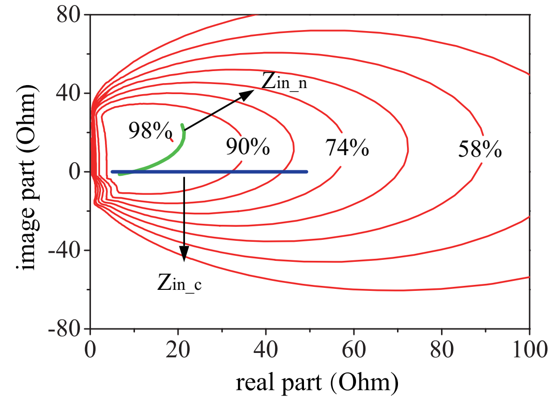

Fig. 7. Efficiency contours of Class E PA when the load of PA varies.

the equivalent impedances at the second harmonic frequency are as small as possible, i.e. (3) is as small as possible when K varies from 0.1 to 0.3. Here, Z_{in_n1} and Z_{in_n2} are the input impedance of Pi network at fundamental and the second harmonic frequencies, and Z_{opt} is the optimum load of PA to obtain highest efficiency. Constrain (a) ensure high efficiencies of PA when K varies, and constrain (b) provides the PA low equivalent load at second harmonic frequency to eliminate the second harmonic content on the transmitting coil.

$$\sum_{K=0.1}^{0.3} |Z_{in\_n1} - Z_{opt}|. \tag{2}$$

$$\sum_{K=0.1}^{0.3} |Z_{in\_n2}|. \tag{3}$$

Z_{in_c} and Z_{in_n} can be analytical calculated, referring to [4]. And then, numerical methods, such as genetic algorithm, can be employed to find the optimum parameters of Pi network to satisfy these two constrains. Here, L_n=390 nH, C_{n1}=800 pF, and C_{n2}=1200 pF are used. The input impedance of the Pi network, i.e. Z_{in_n}, is depicted in Fig. 7. All of Z_{in_n} stay within the high efficiency region, indicating high efficiency of PA even when the coupling coefficient varies in a wide region.

The voltage and current THDs for system with Pi network and full-wave Class E rectifier is presented in Table III. The harmonic distortions are eliminated significantly. The reduction is comparable to the performance of the shunt resonant circuits. However, the system using the Pi network is much robust against the variation of coil coupling. Fig. 8 depicts the system efficiency when the coil coupling coefficient varies from 0.1 to 0.3. The efficiency of the system with shunt resonant circuit decreases as the coupling increases due to the mismatch of PA. While the efficiency of system with Pi network keeps high. The maximum efficiency improvement is 15%.

IV. CONCLUSION

A comprehensive analysis on the harmonic distortions in Class E^2 dc-dc converter is presented in this paper. It shows

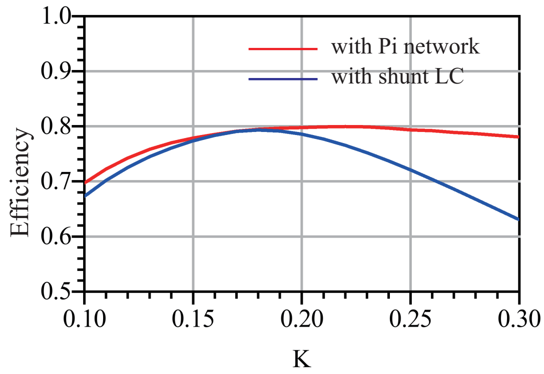

Fig. 8. System efficiency when the coupling coefficient changes from 0.1 to 0.3.

that harmonic voltages and currents on the coils mainly come from the non-ideality of the filter in PA and switching procedure in the rectifier. These harmonic distortions can be reduced efficiently by inserting a Pi impedance transformation network between the PA and transmitting coil and replacing the half-wave Class E rectifier with the full-wave Class E rectifier. The Pi network is carefully designed not only to reject harmonics but also provide the PA predesigned loads. Finally, the improved Class E^2 dc-dc converter is presented, showing a THD reduction more than 42.5% and high system efficiency above 70% when the coil coupling changes.

REFERENCES

[1] S. Y. R. Hui, W. Zhong, and C. K. Lee, "A critical review of recent progress in mid-range wireless power transfer," *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 4500–4511, 2014.

[2] J.-H. Choi, S.-K. Yeo, S. Park, J.-S. Lee, and G.-H. Cho, "Resonant regulating rectifiers (3r) operating for 6.78 mhz resonant wireless power transfer (rwpt)," *IEEE Journal of Solid-State Circuits*, vol. 48, no. 12, pp. 2989–3001, 2013.

[3] K.-G. Moh, F. Neri, S. Moon, P. Yeon, J. Yu, Y. Cheon, Y.-s. Roh, M. Ko, and B.-H. Park, "12.9 a fully integrated 6w wireless power receiver operating at 6.78 mhz with magnetic resonance coupling," in *Solid-State Circuits Conference-(ISSCC), 2015 IEEE International*. IEEE, 2015, pp. 1–3.

[4] M. Liu, M. Fu, and C. Ma, "Parameter design for a 6.78-mhz wireless power transfer system based on analytical derivation of class e current-driven rectifier," *IEEE Trans. Power Electron.*, vol. 31, no. 6, pp. 4280–4291, 2016.

[5] T. Nagashima, K. Inoue, X. Wei, E. Bou, E. Alarcón, M. K. Kazimierczuk, and H. Sekiya, "Analytical design procedure for resonant inductively coupled wireless power transfer system with class-e 2 dc-dc converter," in *2014 IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 113–116.

[6] T. Nagashima, K. Inoue, X. Wei, E. Bou, E. Alarcón, and H. Sekiya, "Inductively coupled wireless power transfer with class-e 2 dc-dc converter," in *Circuit Theory and Design (ECCTD), 2013 European Conference on*, pp. 1–4.

[7] N. O. Sokal and A. D. Sokal, "Class ea new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE J. Solid-State Circuits*, vol. 10, no. 3, pp. 168–176, 1975.

[8] M. Albulet, *RF power amplifiers*. SciTech Publishing, 2001.

[9] S. Aldhaher, P. C.-K. Luk, K. E. K. Drissi, and J. F. Whidborne, "High-input-voltage high-frequency class e rectifiers for resonant inductive links," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1328–1335, 2015.

[10] A. Ahlbom, U. Bergqvist, J. Bernhardt, J. Cesarini, M. Grandolfo, M. Hietanen, A. Mckinlay, M. Repacholi, D. Sliney, J. A. Stolwijk *et al.*, "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 ghz)," *Health physics*, vol. 74, no. 4, pp. 494–521, 1998.

[11] I. C. on Non-Ionizing Radiation Protection *et al.*, "Icnirp statement on the guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 ghz)," *Health physics*, vol. 97, no. 3, pp. 257–258, 2009.

[12] o. N.-I. R. H. IEEE Standards Coordinating Committee 28, *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3kHz to 300 GHz*. Institute of Electrical and Electronics Engineers, Incorporated, 1992.

[13] F. FCC, "Methods of measurements of radio noise emissions from industrial, scientific, and medical equipment," *FCC/OST MP-5*, 1986.

[14] M. Liu, Y. Qiao, S. Liu, and C. Ma, "Analysis and design of a robust class e^2 dc-dc converter for megahertz wireless power transfer," *IEEE Trans. Power Electron.*, vol. PP, 2016.

[15] H.-W. Chiu, C.-C. Lu, J.-m. Chuang, W.-T. Lin, C.-W. Lin, M.-C. Kao, and M.-L. Lin, "A dual-mode highly efficient class-e stimulator controlled by a low-q class-e power amplifier through duty cycle," *IEEE Trans. Biomed. Circuits Syst.*, vol. 7, no. 3, pp. 243–255, 2013.

[16] S. Aldhaher, P. C.-K. Luk, and J. F. Whidborne, "Electronic tuning of misaligned coils in wireless power transfer systems," *IEEE Trans. Power Electron.*, vol. 29, no. 11, pp. 5975–5982, 2014.

[17] S. Aldhaher, P. C. Luk, and J. F. Whidborne, "Wireless power transfer using class e inverter with saturable dc-feed inductor," in *2013 IEEE Energy Conversion Congress and Exposition*, pp. 1902–1909.

[18] A. P. Sample, B. H. Waters, S. T. Wisdom, and J. R. Smith, "Enabling seamless wireless power delivery in dynamic environments," *Proc. IEEE*, vol. 101, no. 6, pp. 1343–1358, 2013.

[19] M. Fu, C. Ma, and X. Zhu, "A cascaded boost–buck converter for high-efficiency wireless power transfer systems," *IEEE Trans. Ind. Informat.*, vol. 10, no. 3, pp. 1972–1980, 2014.

[20] M. Liu, S. Liu, and C. Ma, "A high-efficiencyoutput power and low-noise megahertz wireless power transfer system over a wide range of mutual inductance," *IEEE Transactions on Microwave Theory & Techniques*, vol. PP, no. 99, pp. 1–9, 2017.

[21] M. Liu, M. Fu, and C. Ma, "Low-harmonic-contents and high-efficiency class e full-wave current-driven rectifier for megahertz wireless power transfer systems," *IEEE Trans. Power Electron.*, vol. PP, 2016.