

Letters

An Integrated 6.78-MHz Class Φ_2 Converter Using Bifurcation Phenomenon of Resonance Between the Isolation Transformer

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Abstract—Class Φ_2 (or Class EF₂) reduces the voltage stress of a Class E converter by adding an additional LC branch, which increases the complexity of the circuit. This letter proposes an integrated Class Φ_2 converter that uses the bifurcation phenomenon of the impedance matching network of the isolation transformer to eliminate the additional LC of a typical Class Φ_2 (or Class EF₂) converter. With bifurcation between the isolation transformer, the resonant circuit can be tuned simultaneously at the first, second, and third harmonics, hence achieving a similar quasi-square voltage waveform. Since fewer components are employed, the additional LC can be removed, reducing complexity in comparison to the typical Class Φ_2 (or Class EF₂) converter. A mathematical model has been developed to illustrate the frequency response under the bifurcation status. A 6.78 MHz prototype system has been built to verify the correctness of the mathematical analysis. The experiment demonstrates a lower switch voltage stress similar to the typical Class Φ_2 converter but without using the additional LC. The system has a high efficiency of 90.5% for a megahertz low-power system and exhibits zero-voltage switching independency over the power output range from 3 W to rated 30 W.

Index Terms—Class EF₂ converter, impedance matching network, power amplifier, zero-voltage switching.

I. INTRODUCTION

IN RECENT years, there has been a growing demand for high-frequency converters that offer enhanced power density,

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enhanced efficiency, and reduced electromagnetic interference. Class E, Class F, Class EF, push-pull, and Class Φ converters have emerged as promising solutions to meet these requirements when the converter operates in the megahertz frequency range [1], [2], [3], [4], [5], [6], [7], [9], [10]. These converters offer significant advantages, such as high-power density, over the conventional lower frequency converters. As a result, they have garnered attention in various fields, including power electronics, renewable energy systems, and wireless power transfer [8], [12].

As one of the popular topologies, the Class E converter enables soft switching at megahertz frequencies, leading to lower switching losses [1]. However, it puts greater voltage stress (usually $3.56 \times V_{in}$) on the semiconductors. This increased voltage stress can lead to higher Coss losses and accelerated component aging, impacting the overall reliability and lifespan of the converter [2], [3].

Therefore, in the 1990s, Ingruber et al. [4] proposed to shape the voltage waveform of the Class E converter, Kee et al. [5] summarized and compared Class E, Class F, and Class EF converters, and Phinney et al. [6] proposed to utilize the transmission line theory in radio frequency (RF) referring as the Class Φ converter. Rivas et al. [7] proposed the Class Φ_2 converter based on [6], with the additional LC branch to shape the waveform of the switch with reduced voltage stress (approximately $2.54 \times V_{in}$). This leads to lower Coss losses and harmonic distortion. In addition, the isolated megahertz converter with the Class Φ_2 structure was also developed [8], using the transformer to provide galvanic isolation between the input and the output. Based on a similar theory, the push-pull Class Φ_2 RF power amplifier was also presented [9], [10]; this is able to further reduce the voltage of switches. The Class EF was also developed with soft switching and zero-voltage switching (ZVS) independency against load changes in the wireless power transfer system [11].

However, all these converters typically require the extra LC components to reduce the switch voltage. In the megahertz frequency range, the additional capacitors and both the air- and alloy-core inductors occupy a larger volume and weight, limiting the improvement of power density. In practical megahertz applications, the addition of extra inductors is undesirable. Therefore, a new method not requiring the additional LC components but still able to achieve the quasi-square voltage waveform similar

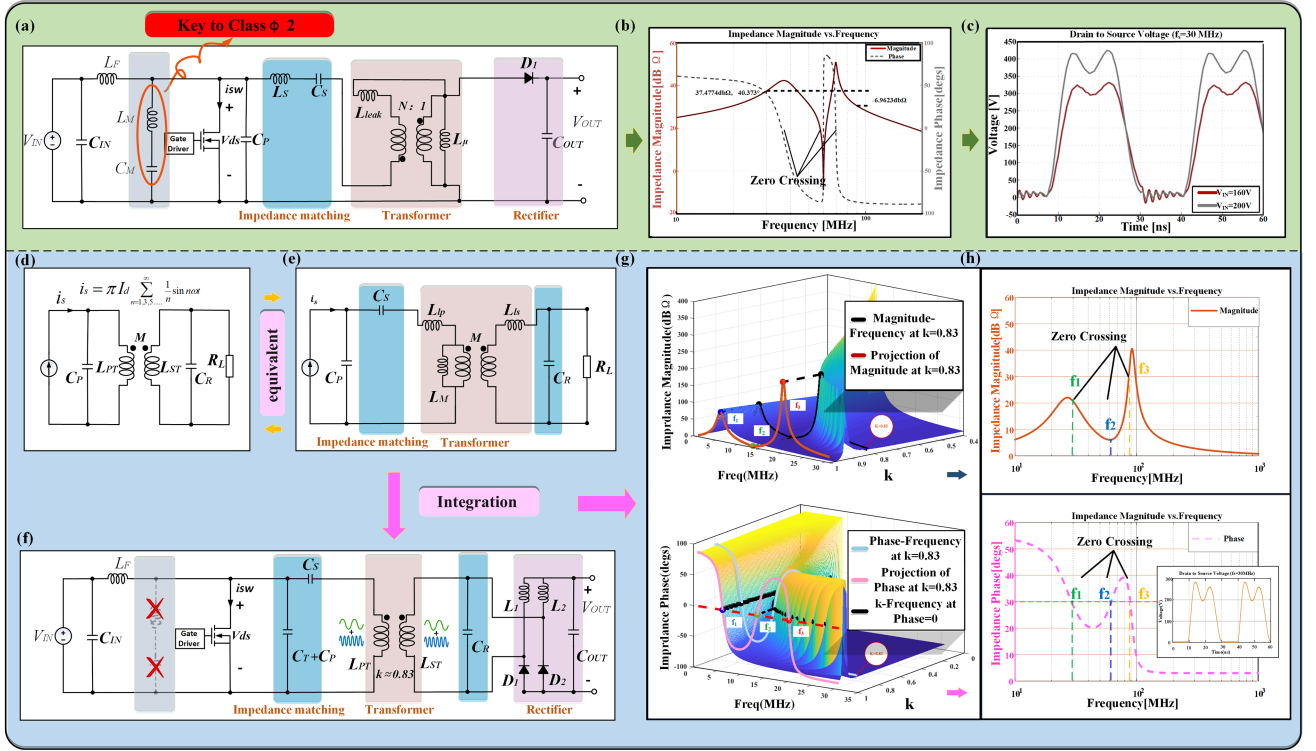


Fig. 1. Proposed system. (a) Typical class Φ_2 system [8]. (b) Impedance and phase angle of typical class Φ_2 [8]. (c) Voltage across the switch of typical class Φ_2 [8]. (d) Isolation transformer with the resonant tank. (e) Equivalent circuit. (f) Proposed integrated class Φ_2 system. (g) Impedance and phase angle against frequency and k . (h) Impedance and phase angle against k near 0.83.

to Class Φ_2 is a research gap, which has not been presented in any of the literature.

In this letter, an integrated Class Φ_2 converter is presented, which leverages the resonance tuning bifurcation phenomenon at the fundamental, second, and third harmonics of the resonant tank. This approach enables the converter to achieve a voltage waveform similar to that of a typical Class Φ_2 (or Class EF_2) converter. However, unlike typical Class Φ_2 (or Class EF_2), which achieves the quasi-square voltage waveform by short circuiting of the second harmonic using the additional LC , the new approach achieves a similar input impedance through simultaneously resonance at the first, second, and third harmonics of the isolation transformer. Notably, the new integrated Class Φ_2 converter eliminates the need for an additional key LC branch, resulting in a reduction in the number of components commonly employed as one of the means to enhance power density.

II. PROPOSED SYSTEM

A typical Class Φ_2 converter (or Class EF_2), as shown in Fig. 1(a), utilizes the additional L_M and C_M branch tuned at the second harmonic. This leads to a corresponding impedance, as shown in Fig. 1(b), and the voltage waveform shown in Fig. 1(c). Consequently, this additional L_M and C_M branch reduces the voltage stress of the converter.

Fig. 1(d) presents the equivalent circuit of the isolation transformer with the resonant tank for achieving the desired quasi-square voltage waveform, where the air-coil transformer

is designed to be tuning to an equivalent coupling near 0.83, hence achieving impedance with zero crossing at fundamental, second, and third harmonics. It is noted that this coupling near 0.83 is specific to this design. Its equivalent circuit is shown in Fig. 1(e); the leakage inductance L_{leak} has been used to resonate with the impedance matching networks C_s and C_p . By carefully tuning the leakage inductance of the isolation transformer, the proposed system exhibits impedance characteristics similar to a typical Class Φ_2 . This can be explained by the bifurcation phenomenon of the tuning network. It is also noted that at megahertz frequency range, air-core inductors are commonly used, which naturally have larger leakage inductances and reduce ac-ac transfer efficiency. This leakage inductance of the transformer can be integrated as part of the impedance matching network. As a result, the circuit can be finally integrated, eliminating the additional LC branch and reducing component count, as shown in Fig. 1(f).

As evident from the mathematical model analyzed in Fig. 1(g), the isolation transformer and the resonant tank tuned at all the fundamental, second, and third harmonics, when k equals 0.83 in this specific design. The projection of impedance and phase is depicted in Fig. 1(h), which demonstrates an input impedance that is similar to the typical Class Φ_2 (or Class EF_2) converter, and able to achieve a similar phase tuning at fundamental, second, and third harmonics without adding another LC branch. These impedance characteristics finally lead to the quasi-square voltage waveform across the switch. Finally, it is noted that the complex waveform originates from

the isolation transformer with the resonant tank. Therefore, the selection of the inverter or the rectifier may affect the system parameter and design, but it would not impact the fundamental principle behind the generation of the quasi-square voltage waveform. The prototype system primarily serves to validate the design and also the feasibility and performance of the new method.

III. MATHEMATICAL MODELING AND ANALYSIS

The system presented in Fig. 1(e) consists of the dc input capacitor, C_{IN} , and inductor L_F ; the capacitors C_P and C_T are connected in parallel with the GaN switch S_1 . A series capacitor C_s is used for precise tuning of the equivalent coupling coefficient and blocking the dc voltage of the converter. R_p and R_s are the equivalent ac resistance of the isolation transformer coils. The power is transmitted through the isolation transformer, which can also have different ratios between the primary and secondary sides. The parallel compensation C_R is also employed before the rectifier to interact with the primary resonant tank for achieving the bifurcation.

The system can then be analyzed in the phasor domain. The impedance of the secondary circuit that reflected to the primary coil is as given by

$$Z_{in} = \frac{1}{j\omega C_p + 1/\left(j\omega L_{PT} + R_p + \frac{1}{j\omega C_s} + Z_r\right)}. \quad (1)$$

The input impedance seen from the primary is as follows:

$$Z_r = \frac{\omega^2 k^2 L_{PT} L_{ST}}{j\omega L_{ST} + R_s + 1/\left(j\omega C_R + \frac{1}{R_{AC}}\right)}. \quad (2)$$

The equivalent load resistance R_{AC} is given by

$$R_{AC} = \frac{1}{\frac{1}{2f_{sw}}} \left\{ \int_0^{\frac{1}{2f_{sw}}} \frac{V_{out} \cdot \pi}{2 \cdot I_{out}} \sin(\omega t) dt \right\} = 4 \cdot R_{DC}. \quad (3)$$

Let the phase angle of the input impedance be zero; then, the phase angle of the input impedance can be calculated as

$$\angle Z_{in} = 0. \quad (4)$$

Neglecting the ESRs of the isolation transformer coils, the output voltage of the system can be given by

$$V_{out} = \frac{\pi V_{in} j\omega k \sqrt{L_{PT} L_{ST}} R_{AC}}{(R_{AC} - \omega^2 L_{ST} C_R R_{AC} + j\omega L_{ST}) Z_{in}}. \quad (5)$$

Fig. 2 depicts the zero crossing of the phase angle for the input impedance $\angle Z_{in}$ in (4), together with the output voltage gain V_{out} in (5), against the operating frequency and k between the isolation transformer. The system will show the frequency bifurcation phenomenon when the coupling coefficient is greater than approximately 0.4, so there are three zero-crossing lines marked as f_1 , f_2 , and f_3 . Noting this bifurcation point at k near 0.4 varies depending on the changes in the system parameters. Specific in this design, at the coupling near k equal to 0.83, the three bifurcation frequencies of the circuit correspond to the fundamental, second, and third harmonics, leading the voltage

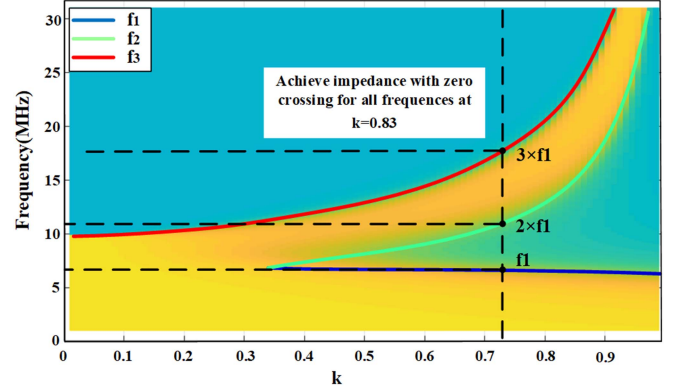


Fig. 2. Bifurcation of the proposed system against k .

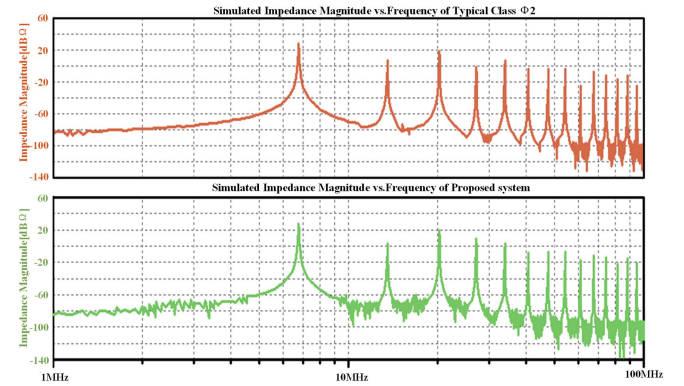


Fig. 3. Comparison in FFT between typical class Φ_2 and the proposed system against frequency.

across the switch S_1 similar to Class Φ_2 , without the additional LC branch.

Fig. 3 presents the fast Fourier transform (FFT) of the typical Class Φ_2 (or Class EF_2) and the proposed system; it can be seen from the figure that both the systems exhibit a low second-harmonic magnitude, which is a typical characteristic of Class Φ_2 (or Class EF_2) implementation.

IV. EXPERIMENTAL VERIFICATION

A 30-W system operating at 6.78 MHz was built to verify the theoretical analysis. The system consists of the converter, the rectifier, and the transformer based on printed circuit board (PCB) coils, as shown in Fig. 4(a) and (b). The input inductor L_F is an air-core inductor, while C_P and C_T are connected in parallel with the GaN switch S_1 . The 710-nH PCB coil provides both the primary and secondary self-inductances, and the winding in different layers of the PCB coils of the prototype system is shown in Fig. 5. C_s is connected in series with the PCB coil for tuning the leakage inductance of the PCB transformer to the coupling coefficient between the coils to achieve zero crossing at first, second, and third harmonic resonance. C_T is the parallel capacitor precisely resonant with the self-inductance of the PCB.

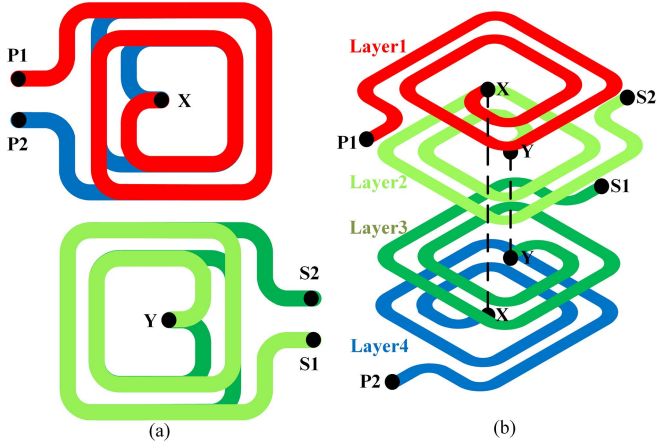


Fig. 4. Design of the air-core transformer. (a) Primary and secondary winding. (b) Winding in different layers.

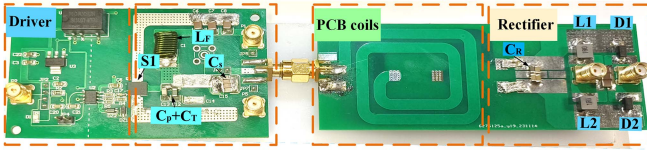


Fig. 5. Proposed integrated class Φ_2 converter.

TABLE I
PARAMETERS OF THE PROPOSED SYSTEM

Parameter	Value	Parameter	Value
L_F	330 nH	L_1	1 μ H
C_T	330 pF	L_2	1 μ H
C_P	390 pF	C_R	1220 pF
C_S	3220 pF	C_{out}	14100 pF
L_{PT}	713 nH	L_{ST}	720 nH
Switch	GS-065-008-1-L	Power diodes	MBR360
V_{in}	30 V	V_{out}	10 V

Finally, the parameters of the components L_1 , L_2 , D_1 , and D_2 are given in Table I. Note that the inverter and rectifier parasitic parameters can affect the soft switching, so adjustments need to be made accordingly when precisely tuning the circuit.

Experiments under conditions of 10%, 50%, and 100% power of 30-W rated power output were conducted, as depicted in Fig. 6. The system achieves a high efficiency of 90.5% that peaked at the full load of 30 W. Noting that the gate driver loss of the switching transistors was excluded from the efficiency measurements.

As shown in Fig. 7, the gate signal and voltage across the switch and the proposed system switch achieved a voltage waveform similar to Class Φ_2 (or Class EF_2), thereby reducing switch voltage stress when compared to a traditional Class E. As shown in Fig. 8, when the load changes significantly from the rated (3.4 Ω) to two times of the rated (6.8 Ω), up to the infinite load (1000 Ω), the ZVS independency characteristics are able to be maintained. In addition, the circuit achieves ZVS

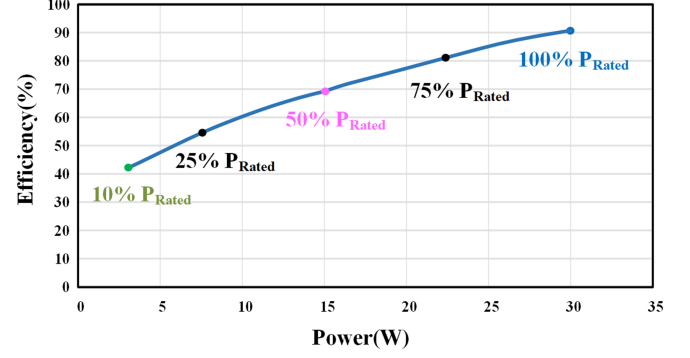


Fig. 6. Power and efficiency of the proposed system.

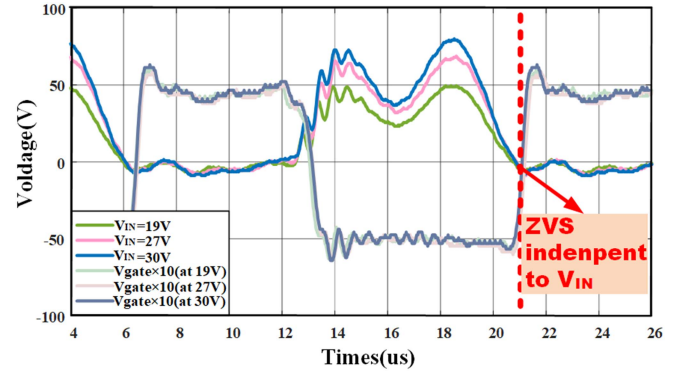


Fig. 7. Gate signal and voltage across the switch as input voltage changes.

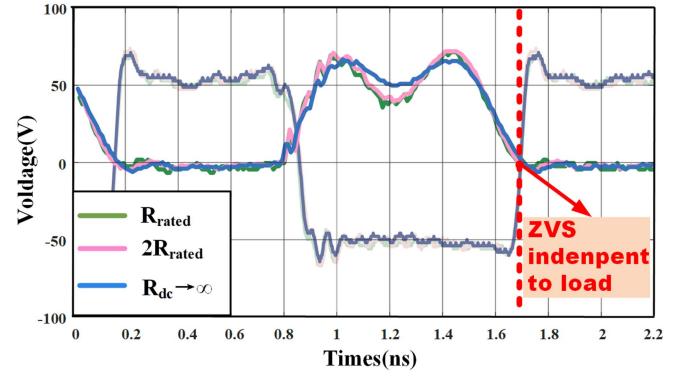


Fig. 8. Gate signal and voltage across the switch as load changes.

soft switching over a wide power range. This is similar to the results discussed in [11].

V. CONCLUSION

In this letter, an integrated Class Φ_2 converter has been presented. The system uses a bifurcation phenomenon of the resonant tank simultaneously splitting at the fundamental, second, and third harmonics to achieve a similar quasi-square voltage waveform to the typical Class Φ_2 (or Class EF_2) converter. Notably, the integrated Class Φ_2 converter has eliminated the additional key LC branch with a concise system

circuitry. A mathematical model has been developed to illustrate the frequency response of the system and the bifurcation of the resonant tank. A 6.78 MHz prototype Class Φ_2 system without the additional key LC branch has been built to verify the system performance. The experimental results show a similar lower voltage stress to the typical Class Φ_2 converter. The system demonstrates a high efficiency of 90.5% for a megahertz-range low-power system and exhibits ZVS independency against the load changes from 3 to 30 W power output.

REFERENCES

- [1] N. O. Sokal and A. D. Sokal, "Class E—A new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE J. Solid-State Circuits*, vol. SSC-10, no. 3, pp. 168–176, Jun. 1975.
- [2] N. O. Sokal, "Class-E RF power amplifiers," *Des. Autom.*, ARRL Tech. Advisor, 2001.
- [3] M. J. Chudobiak, "The use of parasitic nonlinear capacitors in class E amplifiers," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 41, no. 12, pp. 941–944, Dec. 1994.
- [4] B. Ingruber, J. Baumgartner, D. Smely, M. Wachutka, G. Magerl, and F. A. Petz, "Rectangularly driven class-A harmonic-control amplifier," *IEEE Trans. Microw. Theory Techn.*, vol. 46, no. 11, pp. 1667–1672, Nov. 1998.
- [5] S. D. Kee, I. Aoki, A. Hajimiri, and D. Rutledge, "The class-E/F family of ZVS switching amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 51, no. 6, pp. 1677–1690, Jun. 2003.
- [6] J. W. Phinney, D. J. Perreault, and J. H. Lang, "Radio-frequency converters with transmission-line input networks," *IEEE Trans. Power Electron.*, vol. 22, no. 4, pp. 1154–1161, Jul. 2007.
- [7] J. M. Rivas, Y. Han, O. Leitermann, A. D. Sagneri, and D. J. Perreault, "A high-frequency resonant converter topology with low-voltage stress," *IEEE Trans. Power Electron.*, vol. 23, no. 4, pp. 1759–1771, Jul. 2008, doi: [10.1109/TPEL.2008](https://doi.org/10.1109/TPEL.2008).
- [8] J. M. Rivas, O. Leitermann, Y. Han, and D. J. Perreault, "A very high frequency DC-DC converter based on a class Φ_2 resonant converter," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2980–2992, Oct. 2011.
- [9] L. Gu, K. Surakitbovorn, G. Zulauf, S. Chakraborty, and J. Rivas-Davila, "High-frequency bidirectional resonant converter for high conversion ratio and variable load operation," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 3, pp. 1983–1993, Sep. 2020.
- [10] L. Gu, G. Zulauf, Z. Zhang, S. Chakraborty, and J. Rivas-Davila, "Push-pull class Φ_2 RF power amplifier," *IEEE Trans. Power Electron.*, vol. 35, no. 10, pp. 10515–10531, Oct. 2020.
- [11] S. Aldhaher, D. C. Yates, and P. D. Mitcheson, "Load-independent class E/EF converters and rectifiers for MHz-switching applications," *IEEE Trans. Power Electron.*, vol. 33, no. 10, pp. 8270–8287, Oct. 2018.
- [12] M. Pinuela, D. C. Yates, S. Lucyszyn, and P. D. Mitcheson, "Maximizing DC-to-load efficiency for inductive power transfer," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2437–2447, May 2013.