# Wireless Power Transfer for Implantable Medical Devices Using Piecewise Resonance to Achieve High Peak-to-Average Power Ratio

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## Motivation

- **Implantable medical devices** [1] save lives and improve health while **wireless power transfer** is the pre-eminent powering technology for them.
- The in-vivo receivers require **multiple design objectives**: high efficiency, low SAR, easy design, and simple structure.
- **Contribution: we propose a piecewise resonant wireless power transfer system (PR-WPT) to achieve these goals. A high peak-to-average power ratio (PAPR) waveform is generated by a current-mode class D amplifier operating at 6.78 MHz. A 4th-order passive filter is matched to the fundamental and third harmonic voltages of the transmitter, using harmonic elimination for the waveform and closed-form impedance analysis. A full-bridge Schottky rectifier converts the matched voltage into dc. Experiment demonstrates the proof of principle and simulation results show that the piecewise resonant methods can increase the dc output voltage by up to 30%, hence improving the rectifier efficiency. Potential applications for PR-WPT systems are discussed.**

## Methods

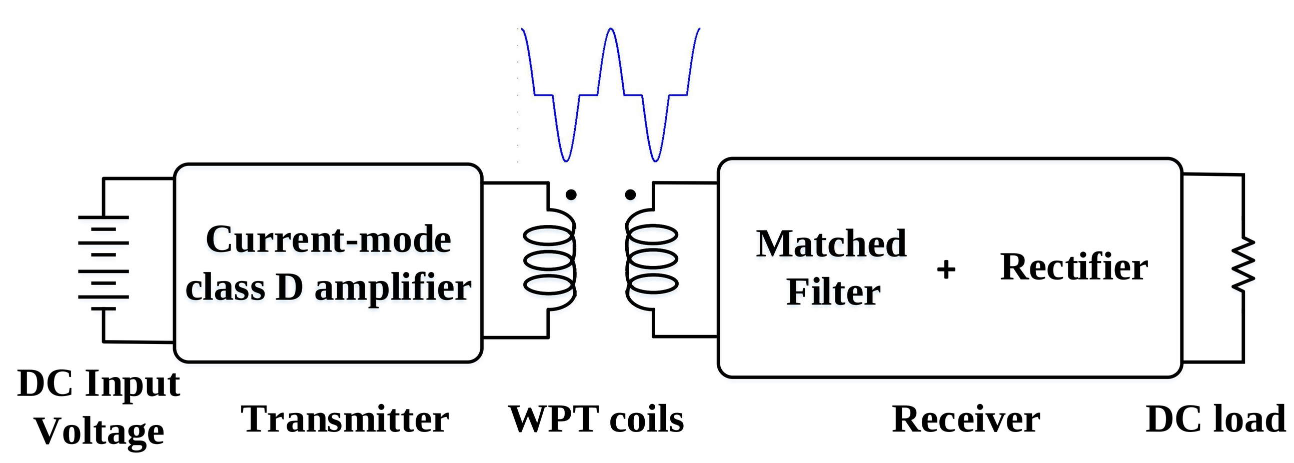



Fig. 1. Piecewise resonant wireless power transfer system.

### 1.Waveform Design and Approximation:

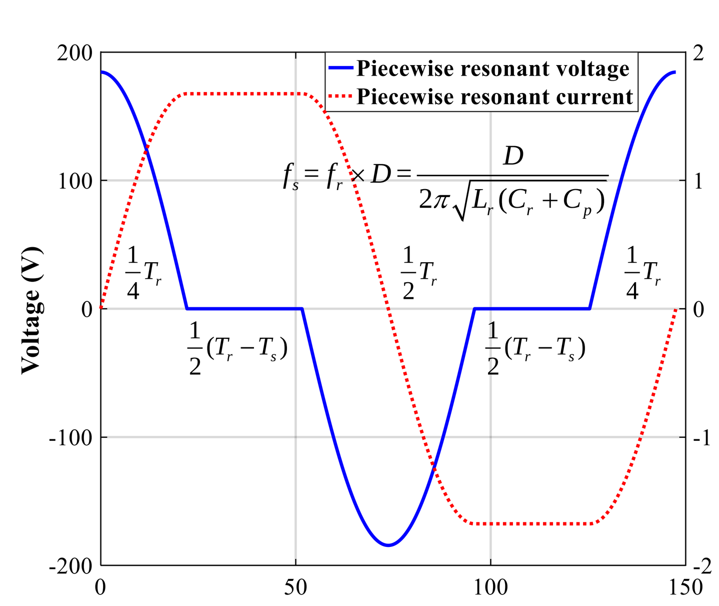



Fig. 2. Piecewise resonant waveforms of primary coil. The voltage is **high PAPR**.

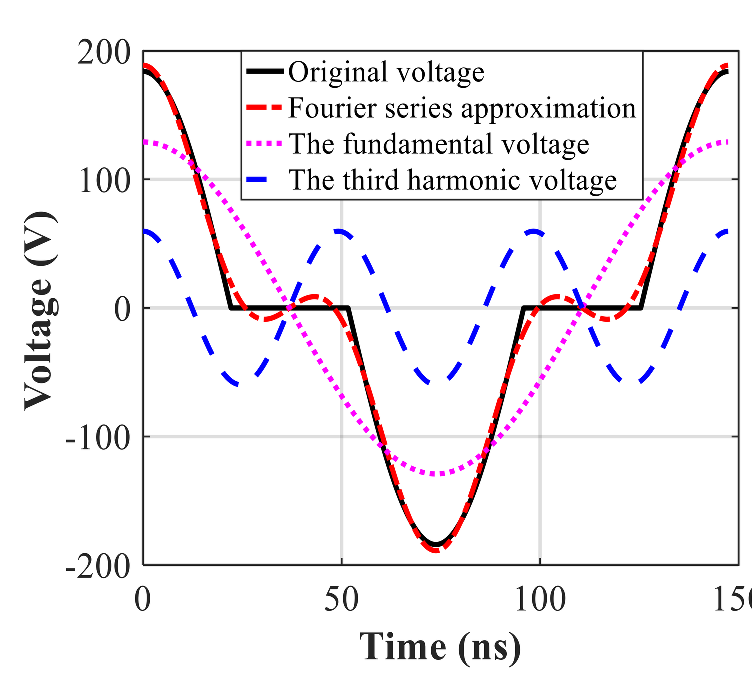



Fig. 3. The piecewise resonant voltage can be well-approximated by the **1st** and **3rd** harmonics when D equals **60%**.

Fourier series expression

$$v(t) = \frac{2V_p}{T_s}\sum_{k=1}^{2k+1}\left[\frac{4\omega_r}{(\omega_r - k\omega_1)(\omega_r + k\omega_1)}\cos\left(\frac{k\omega_1 T_r}{4}\right)\cos(k\omega_1 t)\right]$$
$$= \frac{2V_p}{T_s}\sum_{k=1}^{2k+1}\left[\frac{4D}{\omega_1(1-kD)(1+kD)}\cos\left(\frac{kD}{2}\pi\right)\cos(k\omega_1 t)\right]$$

Approximated expression

$$v(t) \approx 0.7016V_p\cos(\omega_1 t) + 0.3244V_p\cos(3\omega_1 t)$$

### 2. Transmitter and Receiver Design

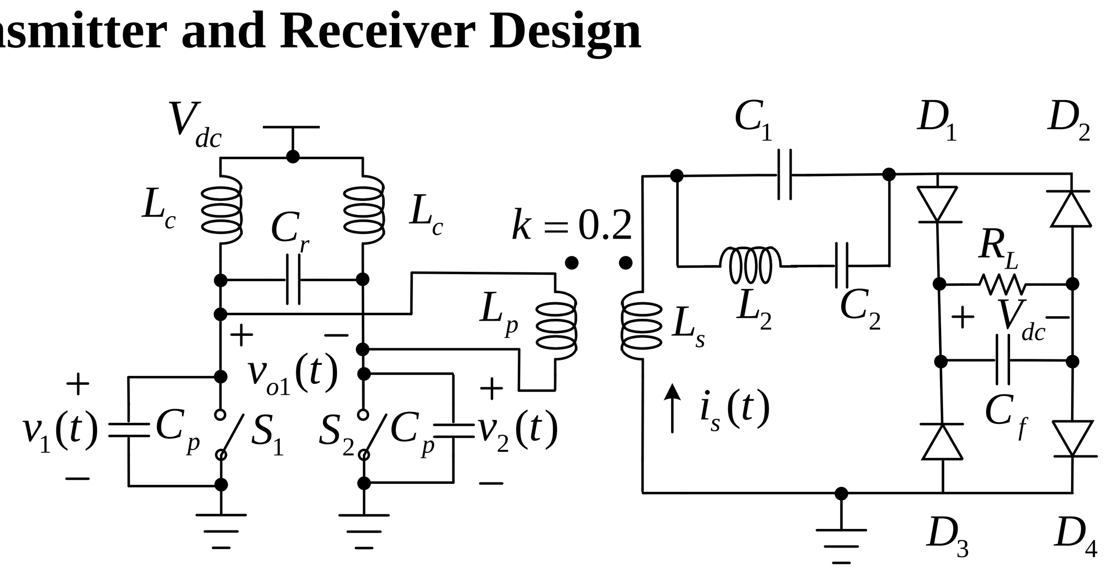



Fig. 4 Current-mode class D amplifier works as transmitter generating piecewise resonant voltage with high PAPR, seen in Fig. 2. Matched filter receives the approximation voltage with 1st and 3rd harmonics, seen in Fig.3. The full-bridge rectifier converts the approximated voltage into dc output.

## Results and Discussion

| TABLE I EXPERIMENT COMPONENT VALUES | | | |
|---|---|---|---|
| $L_p$ | 1.55 µH | $C_r$ | 33 pF |
| $L_s$ | 1.55 µH | $C_1$ | 53 pF |
| $k$ | 0.2 | $C_2$ | 103 pF |
| Diagonal dimension | 70 mm | $L_2$ | 3.57 µH |

### 1. PR-WPT Prototype

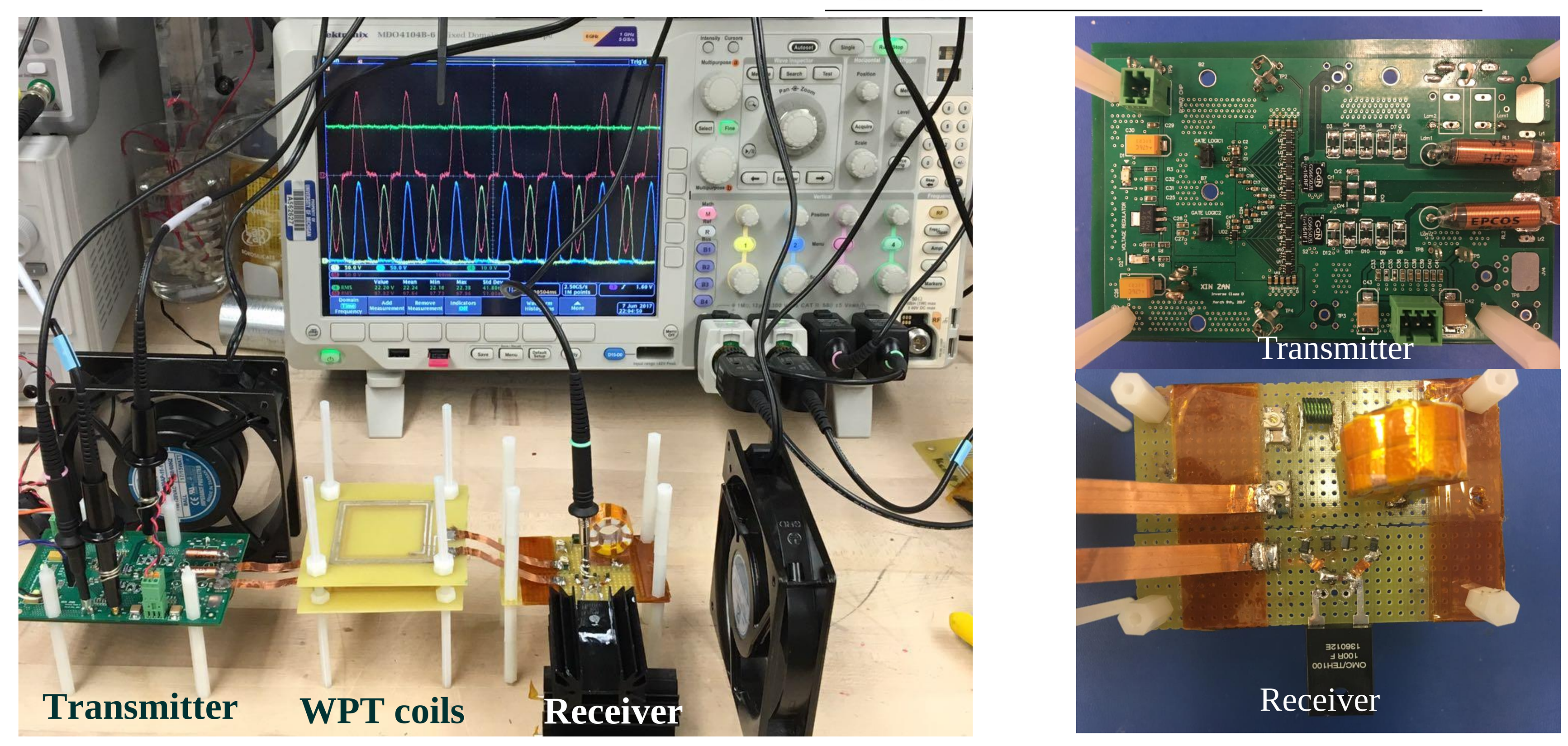



Fig. 5. Demonstration of the PR-WPT system.

### 2. Experimental Results

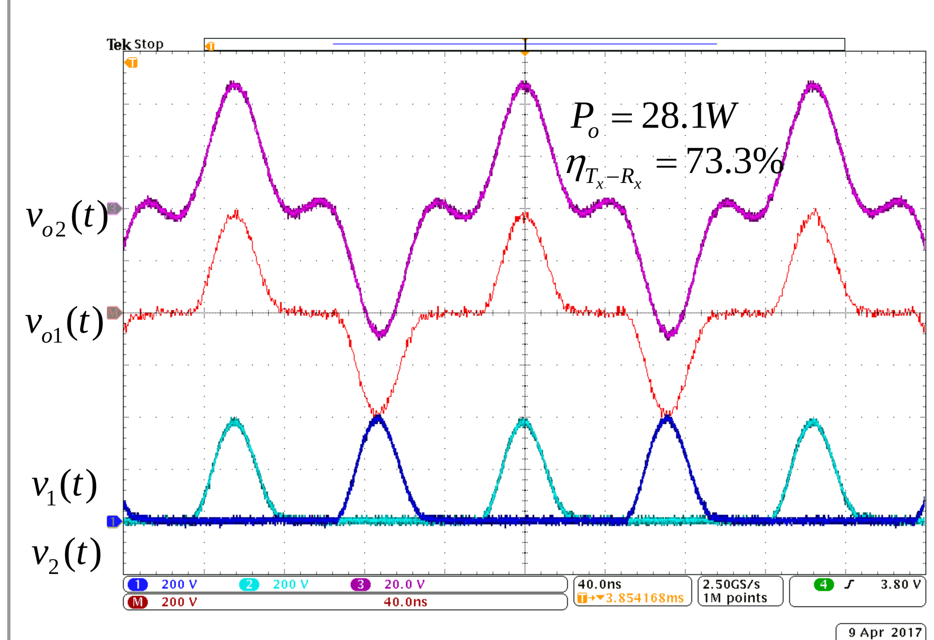



Fig. 6. Experimental results for PR-WPT in Fig. 1 using a resistive load after the matched filter

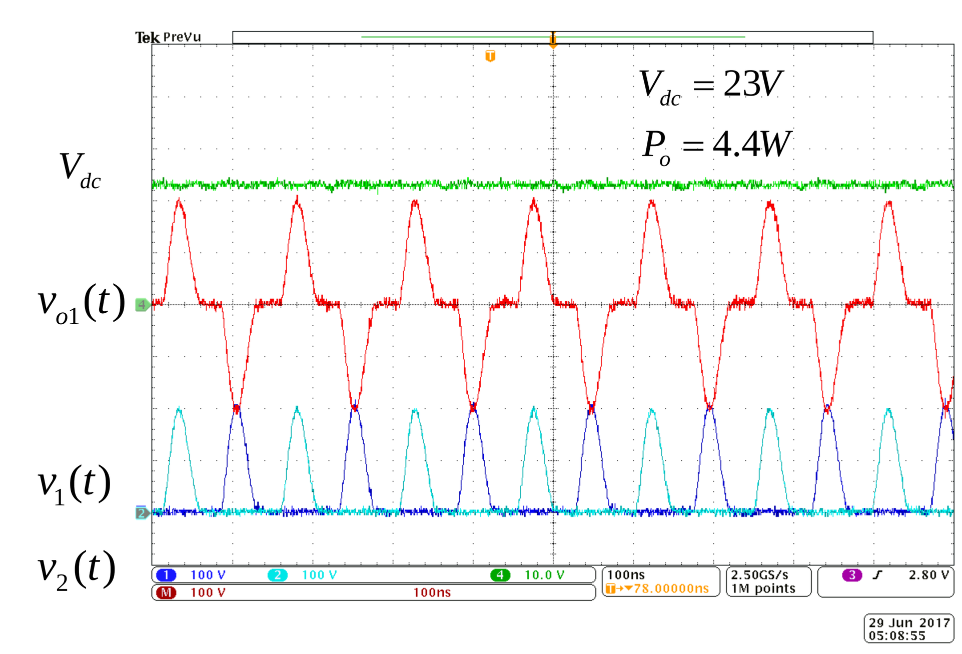
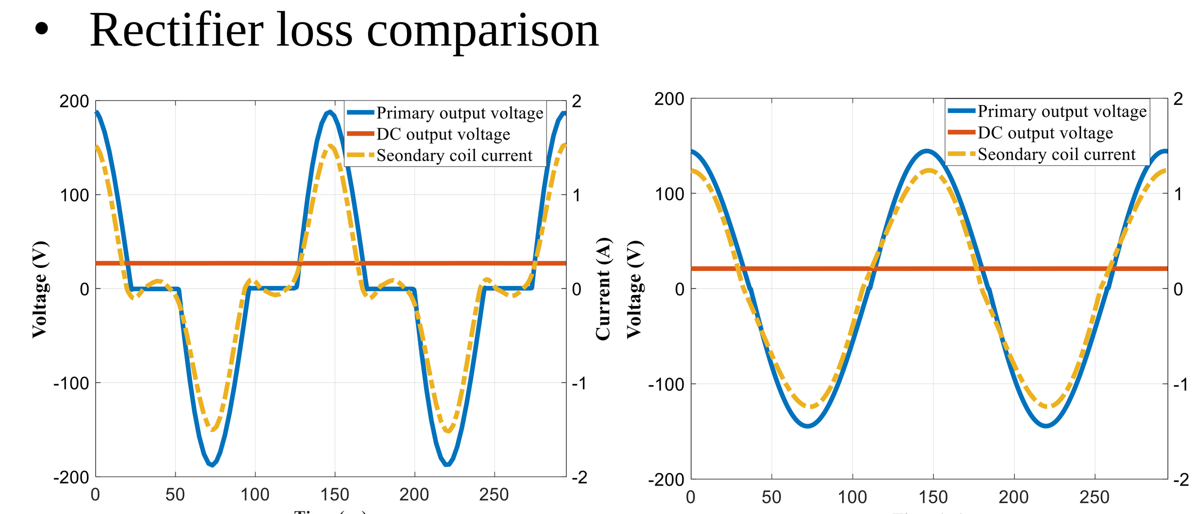



Fig. 7. Experimental results for PR-WPT in Fig. 1

### 3. Receiver Efficiency Analysis

- Rectifier loss comparison




| TABLE II RECTIFIER LOSS COMPARISON | | |
|---|---|---|
| | Sine-wave Resonance | Piecewise Resonance |
| Rms voltage at the primary | $V$ | $V$ |
| DC output voltage | $\frac{\sqrt{2}\pi}{4}kV - 2V_F$ | $\frac{\sqrt{2}\pi}{4}kV \times 1.3 - 2V_F$ |
| DC load current | $\frac{P_0}{\frac{\sqrt{2}\pi}{4}kV - 2V_F}$ | $\frac{P_0}{\frac{\sqrt{2}\pi}{4}kV \times 1.3 - 2V_F}$ |
| Rectifier loss | $\frac{2V_F P_0}{\frac{\sqrt{2}\pi}{4}kV - 2V_F}$ | $\frac{2V_F P_0}{\frac{\sqrt{2}\pi}{4}kV \times 1.3 - 2V_F}$ |

Fig. 8. Sine-wave (SR) and piecewise resonant (PR) systems with ideal switches for the same output power 16 W and primary coil rms voltage 101V, hence equivalent SAR. The PR-WPT system is seen in Fig. 1 while the equivalent circuit of the SR-WPT system with series compensation. Piecewise resonant receiver obtains higher dc output voltage. The **higher dc** output voltage **decreases** the **full-bridge rectifier loss**.

- Efficiency Advantage of Piecewise Resonant Receivers

The receiver for PR-WPT systems requires two additional components for the matched filter compared to a sine-wave resonant (SR) receiver. **The additional inductor** results in more loss, which can be **overcome by decreased rectifier loss**.

$$\beta = \frac{P_{rectifier,loss,SR}}{P_{L_2,loss} + P_{rectifier,loss,PR}}$$

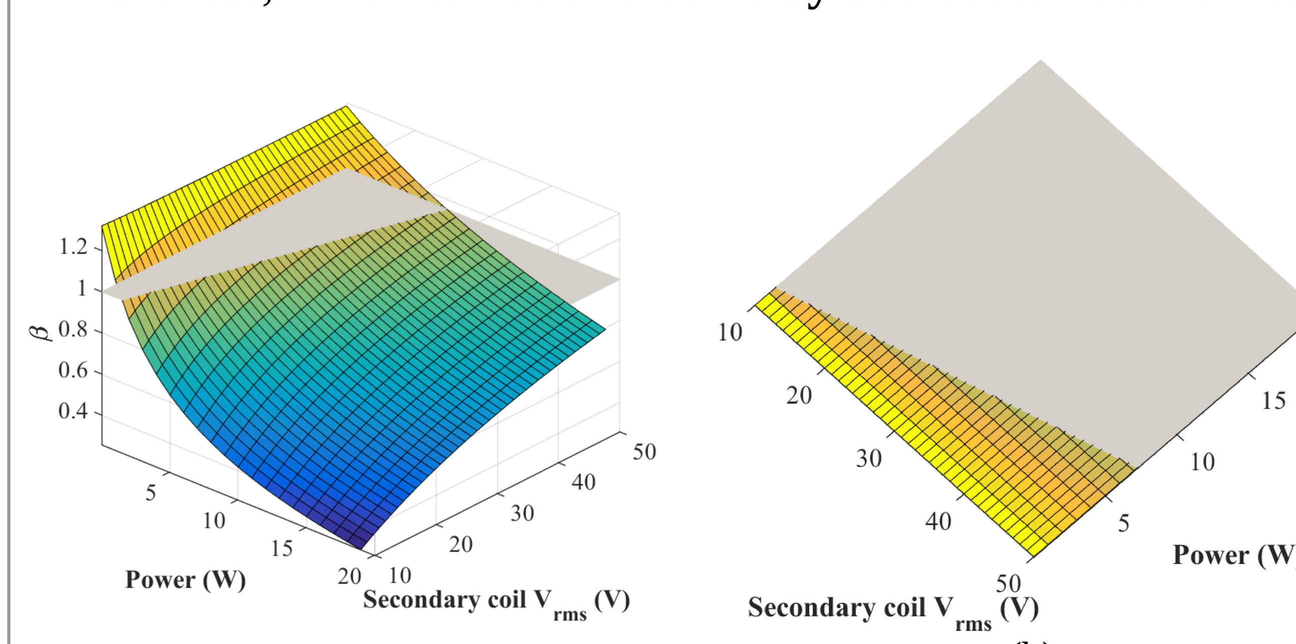



Fig. 9. (a) shows the $\beta$ under different secondary coil rms voltage and output power for implantable medical devices, which is plotted for a Schottky voltage drop of 0.4V The application space for PR-WPT is denoted by the light gridded region in (b). The height of the solid grey plane equals 1, which is the critical criterion.

## Conclusion

High PAPR waveforms using piecewise resonant (PR) methods result in higher dc output voltage and less rectifier loss with an application space that includes **low power and high rms voltage**. A PR-WPT system includes a current-mode class D amplifier which generates a piecewise resonant voltage at 6.78 MHz; a matched filter receives the dominant fundamental and third harmonic voltages, benefiting from harmonic elimination and closed-form solutions to impedance analysis. DC voltage is converted by a Schottky rectifier. **These methods enhance the total performance and design of the receiver in vivo.**

X. Zan and A. T. Avestruz, "Wireless power transfer for implantable medical devices using piecewise resonance to achieve high peak-to-average power ratio," *2017 IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Stanford, CA, 2017, pp. 1-8.

WIMS2 Center for Wireless Integrated MicroSensing & Systems