Coil-Capacitor Circuit Design of a Transcutaneous Energy Transmission System to Deliver Stable Electric Power

Seong-Wook Choi and Min-Hyong Lee

A new transcutaneous energy transmission (TET) system was developed for transmitting electrical power to an implanted device, such as an artificial heart in a patient's body. This new design can maintain a stable output voltage independent of the load resistance. The system includes a compensation capacitor to reduce energy loss and increase power transfer efficiency. Experimental results show that the output voltage of the receiving coil changes very little as the load resistance varies from 14.8 Ω to 15 kΩ, which corresponds to a change in output power from 0.1 to 97 W.

Keywords: Transcutaneous energy transmission (TET) system, impedance compensation, resonance circuit.

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I. Introduction

Operating an implanted electrical device, such as an artificial heart, requires electrical power from a power source outside the patient's body supplied by a protruding electrical wire. Special care is required to prevent infection in the area through which the wire must pass. Although transcutaneous energy transmission (TET) systems have been in development for several decades, these systems cannot be used for the Korean Total Artificial Heart (KTAH, Biomedlab, Korea) because the power consumption of the KTAH changes over a wide range, which causes the output voltages of TET to become unstable. As a result, the TET system for the KTAH needs another device to control their output voltage [1], [2].

Transcutaneous energy transmission systems are devices for transferring electrical power to an implanted device in the body without a penetrating wire [3]-[9]. A TET system should be capable of transmitting its power through about 0.5 cm of skin from the external coil to the internal coil beneath the skin. Therefore, such systems are subject to flux loss, and much of the external magnetic flux does not cross to the internal coil. The portion of the electric energy not transmitted to the internal coil is lost in the internal resistance of the power source or electrical wire. To reduce this power loss and thus increase the transmission power, internal and external TET coils are used in resonant circuits, and TET operates at its resonance frequency [1], [5]. This basic TET concept has high energy transmission capability, but the output voltage changes markedly according to the load resistance [1], [2]. If the load resistance is too high, a very high voltage will be induced in the electrical device which may cause damage.

The power consumption differs markedly between the systolic and diastolic phases in a KTAH and biventricular assist devices (Anyheart, Newheatbio, Korea) [10]-[12]. Therefore, a stable output voltage regardless of the load resistance or output power is a very important requirement for TET. Several TET systems have been developed and tested in continuous experiments to determine whether they can maintain a stable output voltage, but these TET systems need to measure the output voltage of internal TET and transmit the internal voltage to the external TET system [1], [2]. These TET systems require complex, sophisticated controllers and peripheral devices, so they have some risks in terms of their reliability and safety. Therefore, the new TET system is useful because it can maintain a stable output voltage without other peripheral devices. In this study, we designed a new TET system that can supply a stable output voltage independent of the load resistance and, consequently, the output power. We used a push-pull class E amplifier to supply sinusoidal voltage to the TET system, and measured the output voltage of our new system while varying the load resistance. The experimental results were compared with those of theoretical calculations.

II. Model Description and Experimental Results

Figure 1(a) shows a circuit schematic of a standard TET device. If we define $Z_1(\omega)$ and $Z_2(\omega)$ as

$$Z_1(\omega) = j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \text{ and } Z_2(\omega) = j\left(\omega L_2 - \frac{1}{\omega C_2}\right), \quad (1)$$

then, the impedance Z of the TET seen at the power source in Fig. 1(a) is given as

$$Z = \frac{\omega^2 M^2 + Z_1(\omega)Z_2(\omega) + RZ_1(\omega) + R_{\text{in}}\left(Z_2(\omega)+R\right)}{Z_2(\omega)+R}. \quad (2)$$

Here, ω is the angular frequency of the power source; L_1 and C_1 are the inductance and the capacitance of the external coil circuit, respectively; L_2 and C_2 are the inductance and the capacitance of the internal coil circuit, respectively; R is the load resistance; M is the mutual inductance of L_1 and L_2; and R_{in} represents the internal resistance of the power source. When the voltage amplitude of the power source is V_{in}, the current flowing through the external coil circuit (I_{in}) becomes

$$I_{\text{in}} = \frac{\left(Z_2(\omega)+R\right)V_{\text{in}}}{\omega^2 M^2 + Z_1(\omega)Z_2(\omega) + RZ_1(\omega) + R_{\text{in}}\left(Z_2(\omega)+R\right)}. \quad (3)$$

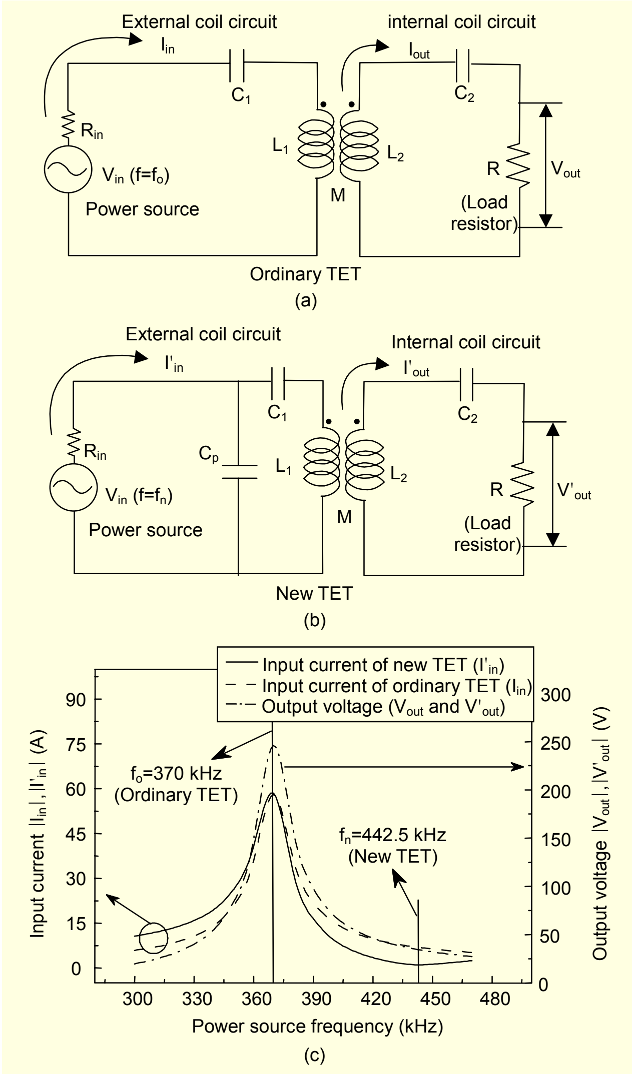

Fig. 1. Schematic circuit diagrams of (a) standard and (b) new TET devices with (c) their calculated input current and output voltage. The solid and dashed lines in (c) represent the input currents of the new and standard TETs, respectively. The circuit parameters are R = 30 Ω, L_1 = 6.6 μH, L_2 = 5.6 μH, M = 1.8 μH, C_1 = 28 nF, C_2 = 33 nF, C_p = 67 nF, R_{in} = 0.05 Ω, and V_{in} = 37.7 V.

The current flowing through the internal coil circuit, I_{out}, can be obtained from the T-representation model of inductive coupling [5] as

$$I_{\text{out}} = \frac{j\omega M V_{\text{in}}}{\omega^2 M^2 + Z_1(\omega)Z_2(\omega) + RZ_1(\omega) + R_{\text{in}}\left(Z_2(\omega)+R\right)}. \quad (4)$$

Figure 1(c) shows the calculated $|V_{\text{out}}|$ and $|I_{\text{in}}|$ as functions of the power source frequency when L_1 = 6.6 μH, L_2 = 5.6 μH, C_1 = 28 nF, C_2 = 33 nF, M = 1.8 μH, R_{in} = 0.05 Ω, and V_{in} = 37.7 V. With these values of L_1, L_2, C_1, and C_2, the resonance frequency, f_O, is calculated as

$$f_O = \frac{1}{2\pi\sqrt{L_1 C_1}} = \frac{1}{2\pi\sqrt{L_2 C_2}} = 370 \text{ kHz} . \quad (5)$$

As the ordinary TET uses this resonance frequency, $Z_1(\omega_O) = Z_2(\omega_O) = 0$; therefore, $|V_{out}|$ can be calculated from (5) as

$$|V_{out}| = \frac{\omega_o MR}{\omega_o^2 M^2 + RR_{in}} V_{in} , \quad (6)$$

where ω_O (= $2\pi f_O$) is the angular resonance frequency. Equation (6) shows that the output voltage is a function of load resistance R. If R or R_{in} is sufficiently low, or ω_O is sufficiently high, then ($\omega_o^2 M^2 >> RR_{in}$), and $|V_{out}|$ is linearly proportional to the load resistance. Under such conditions, as R changes, a high voltage could be induced across the load resistance R, and this may be sufficient to damage the implanted device.

We designed the new TET device shown in Fig. 1(b) to avoid having a high voltage induced across R. The main concepts of the new device are as follows. The operating frequency is not the resonance frequency f_O but is slightly shifted from f_O, which stabilizes the output voltage regardless of the load resistance. In addition, the compensation capacitor C_p is connected in parallel to the external coil resonance circuit to reduce the power loss at the internal resistor R_{in}.

With C_p included in the circuit, the current (I'_{in}) flowing through the external coil of the circuit in Fig. 1 (b) is given as

$$I'_{in} = \frac{\left[\left(Z_2(\omega)+R\right)Z_{cp} + \left(\omega^2 M^2 + Z_1(\omega) Z_2(\omega)\right) + RZ_1(\omega)\right]V_{in}}{\left(\omega^2 M^2 + Z_1(\omega)Z_2(\omega)\right)\left(Z_{cp}+R_{in}\right) + \left(RZ_1(\omega) + R_{in}Z_2(\omega) + RR_{in}\right)Z_{cp} + RR_{in}Z_1(\omega)} . \quad (7)$$

Here, the impedance of C_p is $Z_{cp} = 1/(j\omega C_p)$. The output voltage, V'_{out}, is calculated by the T-representation model as

$$V'_{out} = \frac{j\omega MRV_{in}}{\left(1+\frac{R_{in}}{Z_{cp}}\right)\left(\omega^2 M^2 + Z_1(\omega)Z_2(\omega) + RZ_1(\omega)\right) + R_{in}\left(Z_2(\omega)+R\right)} . \quad (8)$$

If we operate the TET at a frequency of ω_n instead of the resonance frequency ω_O, where ω_n is obtained from the following equation

$$\begin{aligned} & Z_1(\omega_n) Z_2(\omega_n) + \omega_n^2 M^2 \\ & = \left(\omega_n L_1 - \frac{1}{\omega_n C_1}\right)\left(\omega_n L_2 - \frac{1}{\omega_n C_2}\right) + \omega_n^2 M^2 = 0, \end{aligned} \quad (9)$$

then, from (8), the TET output voltage becomes

$$V'_{out} \cong \frac{j\omega_n MR}{\left(1+R_{in}/|Z_{cp}|\right)RZ_1(\omega_n) + R_{in}\left(R+Z_2(\omega_n)\right)} V_{in} . \quad (10)$$

Generally, R_{in} of the push-pull class E amplifier is much smaller than $|Z_1|$, $|Z_2|$, or R. Then, from (10), $|V'_{out}|$ can be approximated as

$$|V'_{out}| \cong \frac{\omega_n M}{|Z_1(\omega_n)|\sqrt{1+R_{in}^2/|Z_{cp}|^2}} V_{in} , \quad (11)$$

where

$$|Z_1(\omega_n)| = \omega_n L_1 - \frac{1}{\omega_n C_1} , \qquad |Z_{cp}| = \frac{1}{\omega_n C_p} . \quad (12)$$

Equation (11) shows that the output voltage is independent of the load resistance at operating frequency ω_n; therefore, we can supply a stable output voltage to the implanted device regardless of its load resistance R. The power consumed by the implanted device, such as a KTAH, is given by

$$P_{cons} = \frac{|V'^2_{out}|}{2R} , \quad (13)$$

which is a function of the load resistance R. Therefore, if the TET device is operated at angular frequency ω_n, there will be a constant V_{out} supply independent of the power consumption of the device.

Figure 2 shows the calculated output voltages, $|V_{out}|$ (ordinary TET using the resonance frequency ω_O) and $|V'_{out}|$ (new TET using the frequency ω_n), as a function of the load resistance. The circuit parameters for the calculation are the same as those in Fig. 1, and C_p is 67 nF. From (9), the calculated ω_n is $\omega_n = 2.78\times10^6$ rad/s; thus, the operating frequency of the new TET is $f_n = 442.5$ kHz as shown in Fig. 1(c). As expected from (6), $|V_{out}|$ of the ordinary TET changes greatly with the load resistance (32.5 V at 3.7 Ω and 1.8 kV at 472 Ω), while the output voltage of the new TET is about 34.7 V and changes very little. This indicates that the new TET can supply a stable voltage to the implanted device independent of the load resistance or the power consumed by the implanted device.

The power transfer efficiency of the TET in Fig. 1(b) is lower than that in Fig. 1(a) because the operational frequency is shifted from resonance. The power transfer efficiency, η, is defined as the ratio between the power supplied by the power source and the power consumed by the load resistance R as

$$\begin{aligned} \eta_o &= \frac{P_{cons}}{P_{supply}} = \frac{I_{out}^2 R}{I_{in}^2 R_{in} + I_{out}^2 R} \\ &= \frac{(\omega_o M)^2 R}{\left(|Z_2(\omega_o)|^2 + R^2\right)R_{in} + (\omega_o M)^2 R} , \end{aligned} \quad (14)$$

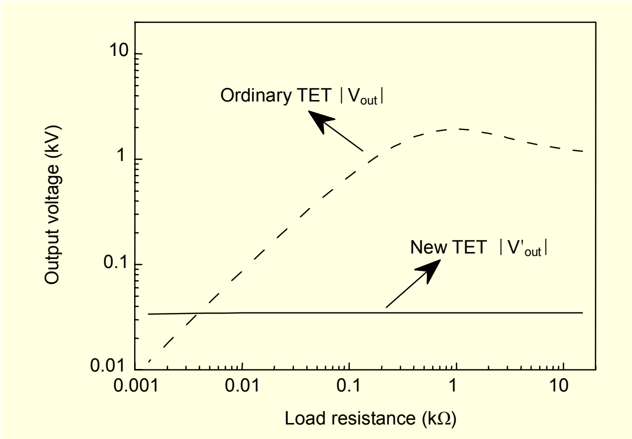

Fig. 2. Calculated output voltage of standard TET (dashed line) and new TET (solid line) for various load resistance values (L_1 = 6.6 μH, L_2 = 5.6 μH, M = 1.8 μH, C_1 = 28 nF, C_2 = 33 nF, C_p = 67 nF, R_{in} = 0.05 Ω, V_{in} = 37.7 V, f_o = 370 kHz, and f_n = 442.5 kHz).

$$\eta_n = \frac{P_{cons}}{P_{supply}} = \frac{I'^{2}_{out} R}{I'^{2}_{in} R_{in} + I'^{2}_{out} R} = \frac{|Z_{cp}|^2 R}{|\omega_n^2 M^2| R_{in} + |Z_{cp}|^2 R}. \quad (15)$$

To increase the power transfer efficiency, it is important to reduce I'_{in} to decrease the power loss in the internal resistor R_{in}. The compensation capacitor C_p is connected in parallel to the external coil resonance circuit for this purpose as shown in Fig. 1(b). Input current $|I'_{in}|$ of the new TET with frequency ω_n follows from (7) and (9) as

$$I'_{in} = \frac{\left(Z_2(\omega_n) Z_{cp} + R\left(Z_{cp} - Z_1(\omega_n)\right)\right) V_{in}}{R R_{in}\left(Z_{cp} - Z_1(\omega_n)\right) + Z_{cp}\left(R Z_1(\omega_n) + R_{in} Z_2(\omega_n)\right)}, \quad (16)$$

$$|I'_{in}| = V_{in} \sqrt{\frac{\left(|Z_2(\omega_n)|^2 |Z_{cp}|^2 + R^2\left(|Z_{cp}| - |Z_1(\omega_n)|\right)^2\right)}{R^2 R_{in}^2 \left(|Z_{cp}| - |Z_1(\omega_n)|\right)^2 + |Z_{cp}|^2 \left(R|Z_1(\omega_n)| + R_{in}|Z_2(\omega_n)|\right)^2}}, \quad (17)$$

where

$$|Z_2(\omega_n)| = \omega_n L_2 - \frac{1}{\omega_n C_2}. \quad (18)$$

Figure 3 shows the calculated $|I'_{in}|$ as a function of $|Z_{cp}|$. Input current $|I'_{in}|$ has its minimum when

$$|Z_{cp}| = |Z_1(\omega_n)| \rightarrow C_p = \frac{C_1}{\omega_n^2 L_1 C_1 - 1}. \quad (19)$$

With the circuit parameters previously defined, the value of C_p that minimizes $|I'_{in}|$ was calculated to be 67 nF. Figure 4

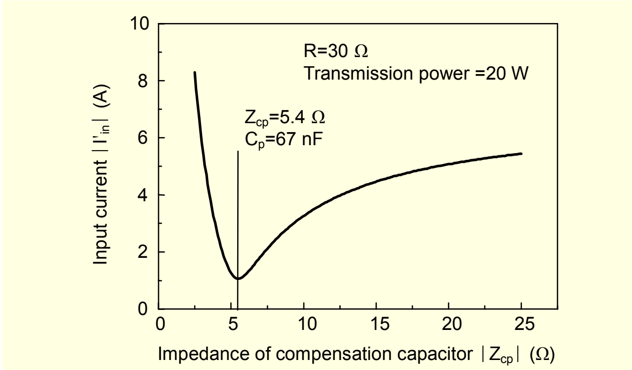

Fig. 3. Calculated input current of the new TET as a function of the compensating capacitor impedance Z_{cp}. The input current has its minimum at $|Z_{cp}| = |Z_1(\omega_n)|$ (L_1 = 6.6 μH, L_2 = 5.6 μH, M = 1.8 μH, C_1 = 28 nF, C_2 = 33 nF, C_p = 67 nF, R_{in} = 0.05 Ω, V_{in} = 37.7 V, and f_n = 442.5 kHz).

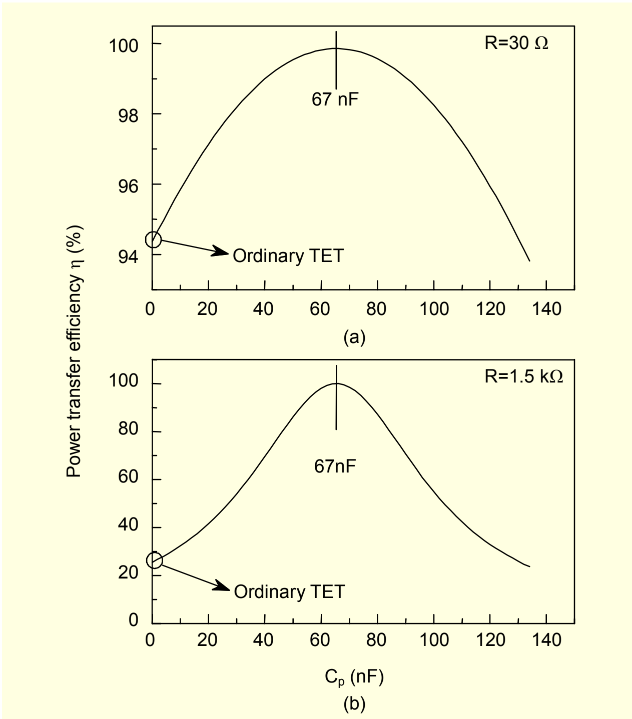

Fig. 4. Calculated power transfer efficiency as a function of C_p at (a) R = 30 Ω (transmission power = 20 W) and (b) R = 15 kΩ (transmission power = 0.4 W) (L_1 = 6.6 μH, L_2 = 5.6 μH, M = 1.8 μH, C_1 = 28 nF, C_2 = 33 nF, C_p = 67 nF, R_{in} = 0.05 Ω, V_{in} = 37.7 V, and f_n = 442.5 kHz).

shows the calculated power transfer efficiency of the standard and new TETs as a function of the compensation capacitor C_p when the load resistance R is 30 Ω or 15 kΩ. The circuit parameters are the same as those in Fig. 1. The ordinary TET, which has no compensation capacitor, corresponds to the point C_p = 0 in Fig. 4. When the load resistance is small, the efficiency of the ordinary TET is not significantly different

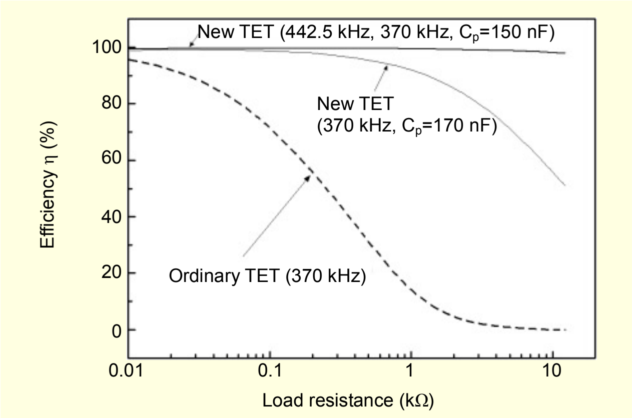

Fig. 5. Calculated power transfer efficiency of standard (dashed line) and new (solid line) TETs as a function of the load resistance ($L_1 = 6.6$ μH, $L_2 = 5.6$ μH, $M = 1.8$ μH, $C_1 = 28$ nF, $C_2 = 33$ nF, $C_p = 67$ nF, $R_{in} = 0.05$ Ω, and $V_{in} = 37.7$ V).

from that of the new TET; however, as the load resistance increases, the efficiency of the ordinary TET decreases markedly while the efficiency of the new TET changes very little. Figure 5 shows the power transfer efficiency as a function of the load resistance R when C_p is 67 nF.

In the experiments, the diameters of the external and internal coils were 55 and 50 mm, respectively. Both coils had 10 turns of Litz wire without any core. The Litz wires consisted of 1,735 thin stands and was 1.5 mm thick. The Litz wires of the external and internal coils were 1.9 and 1.8 m long, respectively. The gap distance between the external and internal coil was 5 mm and the output power was measured with two power meters (WT-230, Yokogawa, Japan). A high efficiency push-pull class E amplifier generated 37.7 V, 370 kHz sinusoidal voltage wave. The amplifier was made with two power metal-oxide-semiconductor field-effect transistors (MOSFET, IRFZ44VZPBF, International Rectifier, USA) and two 100 μH coils. The internal resistance of the push-pull class E amplifier was about 0.05 Ω.

Figure 7 shows the measured (solid squares) and calculated (solid line) output voltages of the new TET as a function of the transferring power. In this experiment, $L_1 = 6.6$ μH, $L_2 = 5.6$ μH, $C_1 = 34.6$ nF, $C_2 = 66$ nF, $M = 1.8$ μH, $R_{in} = 0.05$ Ω, and $V_{in} = 37.7$ V. The operating frequency was 370 kHz, which satisfies (9). The value of C_p to minimize I'_{in} is 150 nF from (15); however, we used a slightly higher value of C_p (170 nF) in this experiment, because the frequency generated by the push-pull class E amplifier used as the power source in our experiment was affected by its loading impedance and the value of C_p; to adjust the frequency to 370 kHz, 170 nF was used instead of 150 nF.

Figure 8 shows the measured (solid squares) and calculated (solid line) transfer efficiencies of the new TET with varying power. The decrease in efficiency at high load resistance is due to the use of 170 nF for C_p, as mentioned above, this is slightly higher than the C_p required to minimize I'_{in} (150 nF). The measured efficiency agrees closely with the efficiency calculated theoretically over a wide range of load resistance.

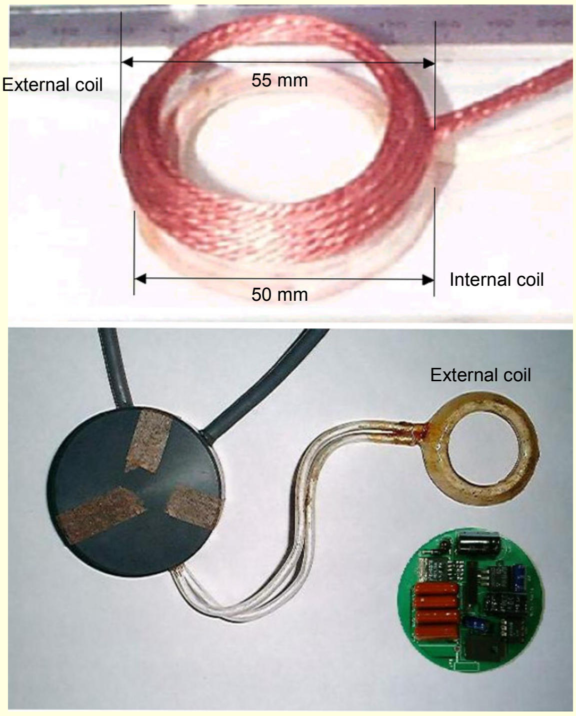

Fig. 6. External and internal coil (top) and TET system (bottom).

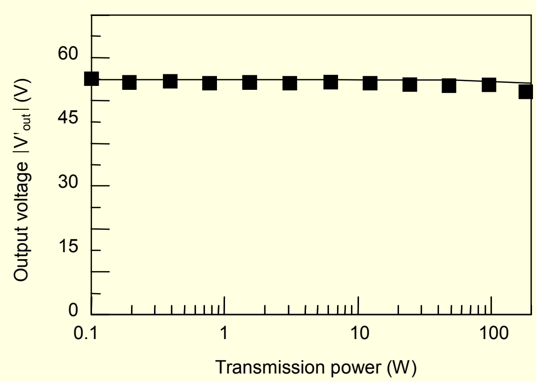

Fig. 7. Measured (solid squares) and calculated (solid line) output voltages of the new TET as a function of power transmission ($L_1 = 6.6$ μH, $L_2 = 5.6$ μH, $M = 1.8$ μH, $C_1 = 34.6$ nF, $C_2 = 66$ nF, $C_p = 170$ nF, $R_{in} = 0.05$ Ω, $V_{in} = 37.7$ V, and f_n=370 kHz).

III. Conclusion

In this paper, we proposed a new TET design to supply a

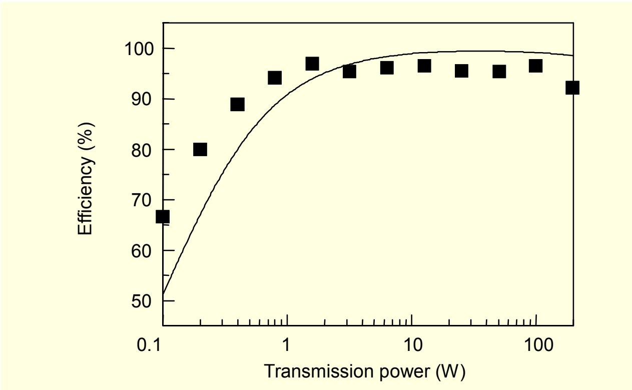

Fig. 8. Measured (solid squares) and calculated (solid line) power transfer efficiency of new TET as a function of power transmission (L_1 = 6.6 μH, L_2 = 5.6 μH, M = 1.8 μH, C_1 = 34.6 nF, C_2 = 66 nF, C_p = 170 nF, R_{in} = 0.05 Ω, V_{in} = 37.7 V, and f_n = 370 kHz).

stable output voltage regardless of changes in load resistance and, thus, the output power. By shifting the operating frequency to ω_n as shown in (9) instead of the resonance frequency ω_0, we can stabilize the output voltage independent of the load resistance. This prevents damage to the implanted device by high induced voltage. We also added a compensation capacitor to reduce the input current and thereby increase the power transfer efficiency. The measured output voltage and power transfer efficiency of our new TET with varying load resistance agreed closely with the theoretically calculated values.

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